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ORIGINAL ARTICLE

Engaging nanotechnology: ethnography of lab-on-a-chip technology in small-scale fluidics research

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Abstract Growth of novel small-scale technologies (micro- and nanotechnology) is expected to change the nature of work in the future. Currently, Human Factors and Ergonomics (HFE) research in small-scale technologies, especially nanotechnology, is in its infancy. Since small-scale technologies are expected to bring about radical changes, aligning HFE to these technologies allows for usable products from the inception, rather than an afterthought. This paper presents an ethnographic study conducted on lab-on-a-chip (LOC) technology in the area of small-scale fluidics. LOC devices are small devices where laboratory processes are shrunk into miniature size, often no bigger than a credit card. LOC technology promises low-cost point-of-care devices in health care, as well as applications in other emerging sectors. In this study, the fabrication and testing of the LOC devices using soft lithography techniques were addressed in detail. Specifically, it is shown that device fabrication in the laboratory entails a considerable amount of skilled workmanship on part of the researcher. Further, this study was conducted at a research laboratory at the University of Waterloo. Addressing laboratory research as a domain of study is a novel venture for HFE. With the growth of universities as major players in the innovation system, the university research laboratory has emerged as an important aspect of the commercialization and technology transfer process. Thus, conducting research in university laboratories will, in the long run, allow HFE professionals to play a greater role in the innovation process linking the university, industry and society. Thus, emphasizing the principle: good economics requires good ergonomics.

Keywords Lab-on-a-chip · Ethnography · University research · Nanotechnology · Workmanship

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1 Introduction

Governments across the world recognize that novel technologies will have a major impact on society (European Commission 2011; Nordmann 2004; Roco and BainBridge 2013; Roco et al. 2013). Similarly, Human Factors and Ergonomics (HFE) researchers note that the advent of these new technologies will change the manner in which work is conducted (Hollnagel 2014). Prominent among these novel technologies is nanotechnology. Nanotechnology research has provided impetus to the development of a large array of materials and devices. These products of nanotechnology are rapidly being employed in a variety of domains, ranging from manufacturing to health care (CPI 2014; Roco et al. 2013). HFE visionaries have also emphasized the role of nanotechnology for the future of society (Karwowski 2006; Szewczyk 2014). Currently, the emphasis of HFE research related to nanotechnology has been largely focused on health (Greaves-Holmes 2012; NIOSH 2013; WHO 2013), possible use of nanomaterials for design ergonomics (Chowdhury et al. 2012), developing countries (Rizvi et al. 2009) and sustainability (Yang and Miao 2010). We expand this list by focusing our work on design of nano- and micro-devices. Specifically, we present two main contributions. First, we present an ethnographic study addressing HFE and nanotechnology in lab-on-a-chip technology (LOC). Second, we offer a new direction for approaching nanotechnology by conducting research in university laboratory settings.

LOC technologies are small-scale (nano- and micro-) systems that typically allow for shrinking multiple laboratory processes onto small-sized chips, at times no bigger than a credit card in size. These laboratory processes may include pathogen detection; DNA analysis; protein analysis, among other applications (for an overview of microfluidic applications of LOC, Streets and Huang 2013; also, Mark et al. 2010). In general, LOC technology holds great promise for global health care by providing low-cost point-of-care (POC) devices. With rapid advances in research, LOC devices blur the boundary between micro- and nanoscale (e.g., Kovarik and Jacobson 2009; Zhou et al. 2015). This blurring is possible by having components at the microscale connected to nanoscale components. In general, the physical and chemical processes required at the small-scale (both microscale and nanoscale) are different from the meso- and macroscale, thus posing novel design challenges for HFE. Hence, in order to successfully design for nanotechnology, it will be necessary to link the nanoscale entities with their usage at the human scale. In short, devising small-scale technologies as well as later using them presents a novel research challenge for HFE.

The ethnographic research study was conducted at a research laboratory at the University of Waterloo. Currently, the University of Waterloo is one of the foremost centers for research in nanotechnology in Canada (WIN 2014). An ethnographic study in a university research laboratory was conducted for two interrelated reasons (top-down and bottom-up). First, in terms of the "top-down" view, in nanotechnology, there is a growing trend of academic research commercialization and technology transfer (Thursby and Thursby 2011; Miyazaki and Islam 2007). In a study of global sectoral innovation systems in nanotechnology, researchers Miyazaki and Islam (2007) highlight that universities account for 70.45 % of nanotechnology-related research (p. 668, also p. 669, Table 3). In terms of patents, Organisation for Economic Co-operation and Development patent database for January 2008 for nanotechnology shows that next to companies, universities own the highest number of patents (Palmberg et al. 2009, p. 61, Fig. 26). Policy theorists (e.g., Etzkowitz and Leydesdorff 2000; Godin and Gingras 2000) have acknowledged the university's leadership in knowledge-based activities, innovation and commercialization. One approach (Triple helix thesis, Etzkowitz and Leydesdorff 2000) has exemplified the university's role in innovation systems in terms of a triple helix comprising of university–industry–government relations. The authors of the triple helix view note that the universities have an increasing role in the national and regional economic development. In other words, universities are often being envisioned as "founts of innovation for a growing economy" (Geiger and Sá 2008, p. 1).

In general, governments around the world are positioning university research commercialization and technology transfer as critical leverage points in their national and regional economic systems (for e.g., see, Veugelers and Del Rey 2014, for Europe; Hughes 2006, for UK; National Research Council 2012, for USA). For example, European policy makers have accentuated the need for addressing university research in the innovation ecosystem (Henriques et al. 2009, pg. 4; also see ERA EC 2008):

> Higher education in the EU-27 accounted for 22 per cent of the total R&D expenditures in 2007, with more than one third of researchers working in the sector (up from 20.6 per cent and less than a third respectively in 2000). It comes as little surprise then that university-based R&D now commands greater policy attention.

Similar to Europe, Canadian policy makers have highlighted Canada's research strength in nanotechnology and the need for successfully linking university, research and industry: "Leveraging Canada's already *significant nanotechnology R&D and education expenditures* into a stronger Canadian nanotechnology industry" (CITC 2011, p. 5, emphasis added; also see, Godin et al. 2002). Understanding the link between university research and industrial sector is vital for understanding how the technology can be made accessible for industrial development (STIC 2013). The Canadian province of Alberta has invested considerably in nanotechnology research at the university level. Alberta's nanotechnology strategy recognizes the role of universities in the growth of nanotechnology and has set up programs such as "nanoAlberta" to promote industry–academic collaboration (nanoAlberta 2007; AlbertaTechFutures 2015). Specific institutions include the National Institute for Nanotechnology (NINT) in Edmonton, Alberta, set up by the government of Alberta and the University of Alberta (nanoAlberta 2007; also NanotechnologyAssetMap 2009). NNIT supports basic research in nanoscience and nanotechnology, as well as includes a research transfer facility for commercialization. Similar to Canada, USA policy makers have also emphasized an enhanced view of nanotechnology research in universities to support innovation (PCAST Nano 2014). A notable example of university–industry–government relations for bolstering the economy is made by the state of Pennsylvania (NTI 2012; also Sá et al. 2008). Six major universities (namely Carnegie Mellon University, Drexel University, Lehigh University, Pennsylvania State University, University of Pennsylvania and University of Pittsburgh) along with other universities and research centers are involved in a statewide scheme of supporting nanotechnology research. Under the Pennsylvanian nanotechnology initiative, 10 research facilities provide support for researchers and companies. Out of these 10 facilities, nine are located at the six main universities named above (NTI 2012, no pagination, under the section "programs"). In all the aforementioned cases of Europe, Canada and USA, universities are prominent actors in the nanotechnology and innovation arena and demand greater attention for improving the commercialization and technology transfer process. Given this emphasis of university research in the innovation system from a top-down view, the laboratories as sources of nanotechnology research demand greater attention. Thus, conducting research in nanotechnology laboratories has implications for HFE in terms of addressing creative research in *bleeding-edge technology* sectors and providing a sustainable transformation to commercial *cutting-edge technology* sectors. In short, HFE professionals can aid in a proactive approach toward successful innovation.

Second, along with the emphasis on the university's role in the national and regional economy, there is a "bottom-up" view of connecting the academic research pathway to commercial pathway for usable products. For example, LOC researchers in health care emphasize the necessity for usable real-world products by connecting academic research and development pathways. Chin et al. (2012) note in a critical survey of existing LOC-based POC devices that despite widespread potential, few of these LOC products have been successfully commercialized. In accounting for this disparity, the authors identify that university research laboratories often conceptualize devices as the end point of academic research:

> For the purposes of meeting milestones and conducting short-term research projects, it may be convenient to treat integration of components as an afterthought. However, such an approach has not led to successful development of real-world products in the past (Chin et al. 2012, p. 2126).

As a solution, the authors highlight the necessity for coordinating academic research and development pathways to successfully sustain commercialization. In order to successfully commercialize LOC devices, the authors mention the need for integration for an overall product rather than specific fine-tuned components. In other words, envisioning integrated end-user products rather than academic research products, thus presenting the need for understanding the dynamics of work conducted in LOC technology in university laboratories, for successful commercialization of POC products. In other words, along with policy-oriented view from the "top-down," this alternative view can be understood as a "bottom-up" view or a "grassroots-level" view in which the HFE researchers address laboratory research in nanotechnology to provide usable and sustainable commercial products, thus emphasizing the view that good economics *requires* good ergonomics.[1]

Currently, the scope of this article involves understanding the dynamics of work in a nanotechnology laboratory, based on the rationale that research in university laboratories is important. Therefore, in this article, the explicit mechanisms of HFE and commercialization are not discussed, as it is beyond the intended scope. In the future, it is expected that as HFE, nanotechnology and laboratory studies proliferate, HFE research can be used to provide sustainable mechanisms to support innovation at a "grassroots-level"; i.e., from "bottom-up." Currently in HFE, studies conducted *on scientific research laboratories as a work domain* are minimal (for e.g., see Jones 2005, for a notable exception; also Jones and Nemeth 2004). This is probably because historically HFE as a discipline has emphasized naturalistic studies of real-life "in the wild," in order to contextualize laboratory-based experimental results. Keeping this view of HFE intact, we emphasize treating the university nanotechnology research laboratory as a work domain where naturalistic studies are to be conducted. Conducting naturalistic studies in the research laboratory will provide a deeper sense of the research practices in nanotechnology, thus in the future, allowing HFE professionals to link the research between academic research products and successful commercialized products. Although research in laboratory settings may be novel for HFE, it is a staple fare in the field of Science and Technology Studies (STS). Typically, the main aim of laboratory studies in STS is in terms of addressing broader concerns of epistemology of science and technology (e.g., Latour and Woolgar 1979; Lynch 1985; Sismondo 2011, Ch. 10). For example, Aurigemma et al. (2013) conducted a study on the design of microfluidic LOC device in a systems biology laboratory. They highlighted the representational practices involved in the LOC device prototyping in biology. In general, their study was conducted to inform broader questions of epistemology: "How do practicing research engineers conduct their work? How does the lab environment continuously support learning?" (p. 119). In contrast, HFE adopts a design approach toward technology. The research conducted in the present paper is toward understanding the generalized research practices adopted for the purposes of design, fabrication and testing using soft lithography techniques for rapid prototyping. It is emphasized that the above distinction between HFE and

[1] The original phrase is "Good ergonomics is good economics." It was the main idea of 1996 HFES presidential address by Hal Hendrick (see Hendrick 1996). Given the scenario of HFE professionals in the innovation ecology, the new phrase is coined inspired by the original.

STS is based on the perceived disciplinary goals from a practitioner's perspective. However, HFE can glean insights from STS in terms of both theories and methodologies for broader understanding of laboratory research as a work domain. As laboratory studies proliferate in HFE in the future, the relation between HFE and STS can be assessed more clearly from an empirical viewpoint.

To summarize, this paper presents two main contributions. First, it presents an ethnographic study addressing HFE and nanotechnology. Second, it presents a direction for addressing nanotechnology in university research settings. In addressing these contributions, the paper is structured as follows. First, we briefly present the backdrop of fluidics research at the small scale. Next, we present the fieldwork methodology and the results in two major phases, fabrication and testing, of making LOC devices in university laboratories. The paper concludes with a discussion of major themes that emerged as salient during the fieldwork, along with possible directions for future research.

2 Ethnographic study

The main goal of the laboratory, in which this ethnographic study was conducted, was to gain a fundamental understanding of micro- and nanofluidics as well as develop LOC technology for biological, chemical and biomedical applications. Soft lithography techniques (described below) were used for fabrication of chips to ensure rapid prototyping for testing research ideas. In the following account, the fabrication and testing of research chips will be developed in detail, as they were common to the research projects underway in this laboratory. The primary goal is to provide a generalized account of the ways in which researchers fabricate the chips and later test them. Once these chips were ensured to function correctly, they were used to gather data for the specific research projects.

2.1 Backdrop of fluidics research at the small scale

Fluidics as a research area studies the flow characteristics of a fluid, in order to be used for operating control systems. In micro- and nanotechnology, precise control and manipulation of fluids are required for fluid flow through small capillaries. The fluids flowing through these capillaries can be manipulated, i.e., they can be mixed, separated or processed. Micro- and nanofluidics is an area of research dealing with fluids at the smaller scale. It is a multidisciplinary endeavor comprising multitude of groups ranging from physicists to engineers. In order to study fluid flow at the smaller scale, researchers in micro- and nanofluidics build devices that have channels at the scale of microns through which fluid flows can be regulated, thus being used for various purposes such as separating cells from its surrounding medium. Researchers in micro- and nanofluidics think of fluid flow in these tubules as analogous to electron flow in electrical circuits. This analogy often allows them to successfully create new devices that blur the boundary between these two domains. At the micro- and nanolevel, fluids behave differently than at the macrolevel. Specifically, the fluid at this level demonstrates laminar flow rather than turbulent flow.

Figure 1 indicates that in turbulent flow, some regions of the fluid move faster than the others, resulting in a flow that is marked with differences in velocity. In contrast to the turbulent flow, in laminar flow, the different layers of the fluid tend to slide smoothly over the others. Thus at the smaller scales, laminar flow presents a marked advantage. For example, the smooth flow allows for identification and/or separation of biological cells from the surrounding medium. Further, fluids at the droplet level can be mixed together to design new materials that could be used in food, beverages and cosmetics. For example, in the area of cosmetics, a French company Capsum has used microfluidic technology (lipidots nanovector technology) from CEA-Leti, a French research institute, to produce cosmetics at a commercial scale (Capsum 2014; Nichol 2013). Lipidots nanovector technology was developed for medical applications. In this technology, the fluorescent imaging drugs are encapsulated in droplets of oil, for delivery to specific cells in the body. Encapsulating active drugs in a

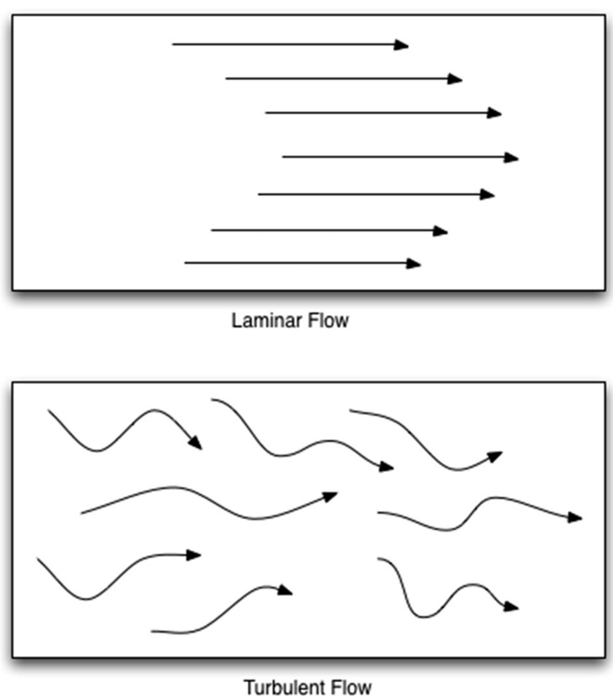

Fig. 1 *Top panel* shows a cross section of laminar flow; *bottom panel* shows a cross section of turbulent flow

fluid-like oil ensures the immiscibility with the surrounding medium as well as allows for providing precise amount of drugs to specific target cells in the body. Capsum has used the lipidots nanovector technology for proper control of fluids to produce biodegradable nano-emulsions that are free from inorganic particles. Therefore, Capsum presents an improved homogeneous product for lotions and creams with improved texture quality. Lipidots nanovector technology is one of the many nano-related technologies that are rapidly being commercialized due to the marked advantages they present in relation to the currently existing technologies.

The technology behind the present LOC devices hails from early microfluidic devices developed for the analysis of biomolecules, biodefense and microelectronics (Whitesides 2006). Later in the 1980s, LOCs were developed for the analysis of aqueous solutions. These early technologies were fabricated using microelectronics that required expensive techniques in terms of time and facilities. These devices provided a major advantage in terms of chemical inertness and high quality of end product. However, due to the time- and location-intensive preparation, the technology for developing these devices proved cumbersome for applications that require rapid evaluation of prototypes. A new method of fabricating microfluidic devices was introduced by Whitesides et al. using soft lithography techniques. This method has acquired widespread usage among laboratories that require rapid prototyping and testing of chips (Kim et al. 2008; Tang and Whitesides 2009).

In the research laboratory, where the study was conducted, multiple research projects, using soft lithography techniques, related to small-scale fluidics were underway. Soft lithography is a family of techniques by which structures can be fabricated or replicated using elastomeric polymers. These polymers, such as polydimethylsiloxane (PDMS), displaying the property of elasticity, can be converted into a stamp or mold for developing micro- or nanostructures. PDMS was also used as a material for fabrication in the laboratory in which this study was conducted. Apart from the reduction in time for prototyping and reduction in costs, the use of PDMS as a material has certain advantages in terms of its permeability, electrical and mechanical properties, among others. PDMS is thermally insulating and is stable up to 300 °C and therefore can be used for applications that require heated solutions. PDMS has insulating properties, allowing it to support embedded electronic circuits. It is generally inert and unreactive toward more reagents, thus allowing for its use with a variety of fluids. PDMS is also optically advantageous for use with microscopes as it is clear and see through after becoming a solid. Further, due to its nontoxic nature, it can be used for biological applications such as mammalian cell growth (Tang and Whitesides 2009). Apart from these marked advantages, PDMS also displays certain drawbacks. At times, PDMS presents incompatibility with certain fluids, i.e., it has a tendency to swell or react adversely with certain organic chemicals (van Dam 2006, Ch. 3). Despite these challenges, PDMS is viable material for research in small-scale fluidics because of its rapid prototyping capabilities and lower cost.

Along with using PDMS as a cost-effective material for prototyping, fluidics laboratories also reduce the overall cost of research by conducting research in normal laboratory facilities rather than in “clean room facilities.” Clean room facilities are environments used for scientific research with low levels of contaminations and controlled amount of pollutants, such as dust. To work in a clean room facility, researchers wear a clean room suit to avoid contamination. Clean room facilities are often mandatory for research in the areas such as semiconductors. Typically, the price of operating and using a clean room is quite high. As an example, the clean room facility in the G2N laboratory in the University of Waterloo has an access rate of CAD$ 3200 for external users and CAD$ 1600 for academic users per term (G2N 2014). Since the prototyping of devices in small-scale fluidics is possible without the stringent requirements of clean room facilities, researchers often conduct their research in normal laboratory facilities that are still highly clean.

2.2 Fieldwork methodology

In this study, the primary procedure adopted was observations, coupled with informal discussions for additional knowledge gathering. As the first step, the ethics approval was received from the Office of Research Ethics, University of Waterloo. Next, the fieldwork was entirely conducted by one person (first author). In all, there were six researchers whose work was observed in great detail. Among these six, five researchers were graduate students. Out of these five, four were PhD students and were in their advanced stages of PhD research, whereas one student was a final year masters level student. Apart from these five researchers, the final researcher was an upper-year undergraduate student involved in a project with one of the above-mentioned PhD researchers. These researchers were from varied engineering backgrounds. For example, two researchers were from mechanical background and were conducting experiments in fluid flow in LOC devices. Two others were from electrical engineering background. Their projects involved application of microelectric current to the fluid flow to produce novel LOC devices. One member of the laboratory was from a thermal engineering background and was studying flow characteristics of various fluids. Finally, the undergraduate researcher was from the mechanical engineering background and was helping one of the researchers (from mechanical engineering background). In general, the laboratory also had other projects related to fluid dynamics at the smaller scale for biological applications and there were few researchers from chemical engineering and biotechnology involved in these projects. These other projects were not followed in detail because the individual researchers did not grant permission for observation and interviews.

At the site, the laboratory work was observed for 2.5 months (last week of March 2013–first week of June 2013). The overall official time spent in the laboratories amounted to approximately 94 h. Since researchers worked on individual projects, researchers were followed one at a time and their projects were observed in depth, before moving onto other projects. Since the area of research in HFE and nanotechnology is novel, rather than concentrate on the details of any specific project, the aim was to identify a generalized understanding of the laboratory work done in LOC technology. The conceptual development of the dimensions of activity observed in this laboratory was developed and refined over the course of time the research project was underway.

To place the research conducted in this laboratory from a broader perspective, the understanding received from observations was supplemented with informal discussions with other graduate students, in other laboratories in micro- and nanofluidics, at the University of Waterloo. These informal discussions were about the nature of their work as well as micro- and nanofluidics as a general research area. Along with the informal discussions, attending seminars and lectures in the University of Waterloo also provided an overall sense of the research area of LOC technology.

2.3 Laboratory setup

In order to understand the activities involved in making LOC devices, the first step requires highlighting the layout of the equipment vis–à–vis the processes of fabrication and testing. The laboratory space was divided into two main regions A (A1, A2) and B (Fig. 2). Section A constitutes the area where the LOC chips are fabricated, and the Section B is where they are tested. The fabrication process dealt with chemicals as well as processes that required certain specialized equipment. This suite of equipment was placed in section A in a manner that facilitated the fabrication process as well as provided adequate safety. Specifically, A2 was the place where the chemicals were handled, whereas A1 was chemical free.

In general, the area A consisted of spin coaters, hot plates, plasma chamber, vacuum chamber, UV exposure system, fume hoods and various glassware and tools. Apart from the above listed equipment, this laboratory also had other tools and devices not discussed here, as they were not involved in the activity of fabrication. In area A, A1 is a small room that houses a UV exposure system and a small workbench. In area A2, the major chemical processes are conducted in the fume hoods. The other devices are used as the fabrication process progresses. In contrast to the fabrication processes conducted in area A, area B was used for testing the devices earlier fabricated in area A. In case of Section B of the laboratory, chemicals were not present. The finished devices were tested in Section B using the microscope, pressure controllers and computer software for recording data. This separation between the laboratory sections provided adequate safety and facilitated the research activity.

2.4 Laboratory safety

Along with the above setup, safety was a key concern in the laboratory. Researchers working in the laboratory had to undergo safety training. Researchers used glasses, gloves and laboratory coats to ensure precaution during work hours. There were eyewash stations as well as steps outlined about what was to be done in case of an emergency. While dealing with harmful chemicals, individuals in the process of making LOC devices took utmost care during the fabrication process as well as during the testing process.

Typically, there are considerable safety risks involved in making LOC devices. Working with chemicals required wearing latex gloves all the times. Sometimes, in order to handle dangerous chemicals, extra pair of gloves was worn by the researchers. Laboratory coats were also worn at all times in the laboratory. While working with chemicals, safety glasses were worn. All handling of dangerous chemicals were done under the ventilated fume hood. Further, the laboratory had eyewash facilities; the area surrounding it was kept free at all times. There were also emergency contact numbers and a phone available in the laboratory.

2.5 Fabrication

Figure 3 demonstrates the generalized steps in creating and testing a LOC device. These activities involved in these steps are addressed in greater detail in the following subsections. The overall generalized laboratory activity related to LOC devices is divided into three main subprocesses: Concept design (Sect. 2.5.1); Prototyping (Sect. 2.5.2) and Molding (Sect. 2.5.3); along with, Testing (Sect. 2.5.4).

2.5.1 Concept design

The first step of LOC fabrication is governed by an engineering approach in which the whole device is conceptualized. Researchers use computer-aided design (CAD) software programs to conceptualize the device. In this step,

Fig. 2 Functional setup of the laboratory where the study was conducted. The laboratory was divided into parts *A* and *B*. Part *A* served as the area for fabrication. Part *B* served for testing the fabricated LOC devices

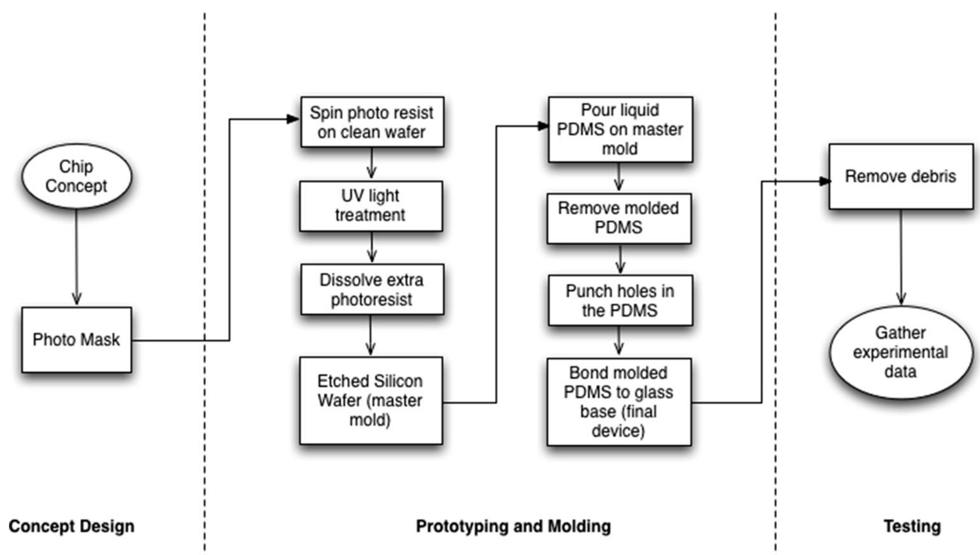

Fig. 3 Steps involved in creating and testing of the LOC devices. The three major subprocesses include Concept design; Prototyping and Molding; Testing

the researcher envisions the final device in terms of the overall functions and detailed structure. These structural formulations require knowledge of laws of fluid dynamics. Using scientific formulas, the flow rates and permissible pressure across the channel are calculated. Based on the calculations of flow, the resistance provided by the channel is calculated. These resistances and fluid flow are optimized in terms of the entire device architecture. LOC devices can be made based on different technologies such as fluidics, electronics, among others or a mixture of those technologies. For example, the devices can be based on a mix of electrical and biological networks embedded in the device. However, in this particular laboratory, where the study was conducted, the researchers focused on devices with a "passive geometry"; i.e., the setup of the channels in the device was manipulated, to receive the appropriate function at the device level. In other words, manipulation and proper design of the channels allow for the fluids to be mixed, separated or processed.

Once the researcher holistically conceptualizes the overall device, the first step toward fabrication involves "thinking in terms of layers." In order to fabricate the device, all the necessary channel architecture is conceived in terms of their heights from the base of the device. All the features at the same height are conceived to be existing in the same layer. Further, different materials can be deposited layer after layer to make complex devices such as a mix of fluidics and electronics. Taken together, these layers constitute the device architecture. Once the layers divide the device in terms of layers, these layers are printed in high resolution onto a transparency film, to create a photolithography mask. This mask is opaque and allows light to shine through based on definitive patterns. In this process, the UV light transfers the pattern present on the mask to the wafer. These masks can be understood as negatives that allow UV lights to pass through and thus transfer their pattern onto the device. Since these photomasks are crucial for the device quality, this particular fluidics laboratory sent its CAD drawings to an external vendor, located in USA, who provided the photomasks. The turn around time for this process was typically about 5 days.

2.5.2 *Prototyping*

After the researchers obtained the photomask, the steps toward prototype development are taken. The result of this prototype development phase is a "master mold." The "master mold" is a silicon wafer that has the desired device channels and structures that can be used repeatedly to form batches of devices. The first step in developing the prototype is the spin coating of a negative or positive photoresist on a *clean* silicon wafer. The emphasis on clean is of crucial importance in nanotechnology device fabrication, in general. In fabricating LOC devices, dust plays the role of the adversary. Dust particles may not be completely viewed by the naked eye but is detrimental for the fabricated chips. As mentioned before, fabrication requires dust free environments, "clean room" facilities, specially designed to support nanotechnology research. However, the maintenance and use of these facilities often incur extensive costs. To reduce costs as well as improve rapid prototyping, researchers conduct their work in normal laboratory settings. However, they ensure that the laboratories are very clean. Further, before using silicon wafers for the "master mold," they clean it up by a blast of high-pressurized clean air, thus ensuring that any dust particles are removed. The chemical processes involved in the fabrication are typically conducted in a fume hood.

After cleaning, the silicon wafer is coated with a calculated amount of photoresist material. Photoresist materials are polymer-based resins, sensitive to ultraviolet (UV) light. In order to be usable, they should have a property of being sufficiently viscous, i.e., to ensure proper coating of the wafer. At the same time, after exposure to the UV light, they can be removed. Photoresist materials can be either positive or negative (depends on the procedure). A positive photoresist produces an image that corresponds to the image of the mask. Once it has been chemically reactive with the surface of the wafer, the exposed regions are made soluble and removed. In contrast, the negative photoresist works just the opposite. At the end of the photoresist treatment process, as a result of the photoresist treatment (positive of negative), the structure of face of the wafer is changed, thus presenting new opportunities for working with the wafer. For example, the wafer was transformed from having a plain face to one having grooves or channels etched into it. These chemical transformations allow the researcher certain ways of dealing with the materials at a perceptual level that was not possible earlier. In other words, the silicon wafer which did not afford the activity of molding earlier provided opportunities for novel engagement after the chemical transformation; it became workable.

At the same time, along with the workability of the photoresist material, there is considerable skill required on the part of the person involved in the fabrication process. Dexterity is most visible in the coating process. Coating the photoresist on the spin coater is not a straightforward process. The spin coater is a device with a turntable that spins at a very high speed. For example, when a glass slide is placed on the turn table and the required amount of photoresist is poured into it and made to spin, the material spreads all over the wafer in an even manner due to the centrifugal force induced by the spinning. In an ideal scenario, the spin coater produces an even coating. However, as the observations revealed, the even coating was largely the product of the skill of the fabricator.

To make the previous statement intelligible, consider the example of a glass slide that is to be spin coated on the turntable. Imagine that you are looking at it from above. The task at hand is to pour the photoresist on a glass slide and to coat it evenly. The quantity of photoresist material for a fixed thickness of coating is generally calculated initially, but actually getting the appropriate thickness remains a challenge. This main challenge is faced by the person in a situation *where* the photoresist material has to be poured on the glass slide so as to ensure an even surface coating in all directions. Finding a solution to this problem is not straightforward. The challenges that the researchers face in the process can be broken into two subcomponents. First, the glass slide has to be properly aligned with the turntable. Second, the photoresist material has to be applied in a manner so that the coating is even. For the first problem of alignment, different researchers approached the problem differently. Some researchers used to place the slide on the static turntable with careful precision to ensure the fit before starting the turntable rotation. Another participant placed the glass slide carefully in the middle and rotated it for some time so that the centrifugal force aligns the glass slide to the turntable. A third researcher focused on the area that would pertain to the extreme end of the rotating slide. The logic employed by the third researcher was simply that the two ends of the glass slides would chart the same arc while rotating. This step was repeated for another arc corresponding to the antipode of the previous area or the rotating slide or wafer. If the two extreme edges subsequently chart the same arc in the area of interest, then the glass slide is centrally aligned. This strategy employed by the third researcher can be explained with the help of Fig. 4. In Fig. 4, if the glass slide is aligned centrally on the turn table, then point A should chart the same arc as point B. To ascertain that the glass slide is placed properly, the researcher notices points A and B while the slide is rotated on the turn table. When the points A and B chart the same arc, then the researcher decides whether the glass slide can be said to be centrally aligned.

Once the wafer is aligned, the next step involves the placement of the photoresist material such that the spread is even over the surface. This step also poses a problem. Returning back to the example of the glass slide, imagine pouring the material in the middle. Rotation of the turntable, in this scenario, provides a distribution that is proper in the middle but tapers toward the ends of the scenario (Fig. 5a). A different method could involve placing the material on the glass plate, in terms of a middle long line (Fig. 5b). This method produces a crisscross pattern of alignment and at times may cause uneven deposition on a few sides. There is no one best manner of spin coating that ensures a proper outcome. However, individuals devise their own optimal methods. One method, even though a bit painstaking provided a more even finish than the others. In this method, the researcher poured the material in three places in varied amounts before turning the turntable (Fig. 5c). This researcher's method of making two centers and connecting them with a bridge led to a more even spread of the material over the glass slide. Along with this method, the researcher also mastered the amount of the material to be placed at these locations to ensure an even spread. The challenge of coating the glass demonstrates the hidden dimension of workmanship that exists in laboratory research in LOC technology.

In summary, coating a wafer with the photoresist is not a simple act but can be conceptualized as a resultant of an interaction between the material, the external forces applied by the spin coater and the dexterity of the researcher.

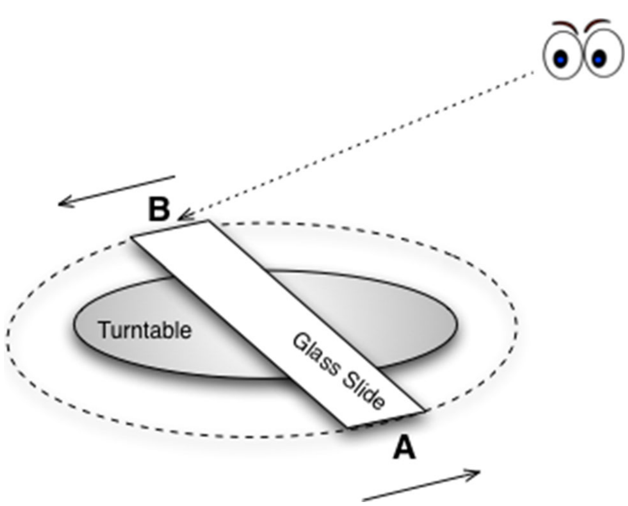

Fig. 4 Figure shows two points *A* and *B* when the glass slide is laid on the turntable. The researcher ascertains that the slide is centrally aligned when the two extreme edges of the slide (*A*, *B*) chart the same arc

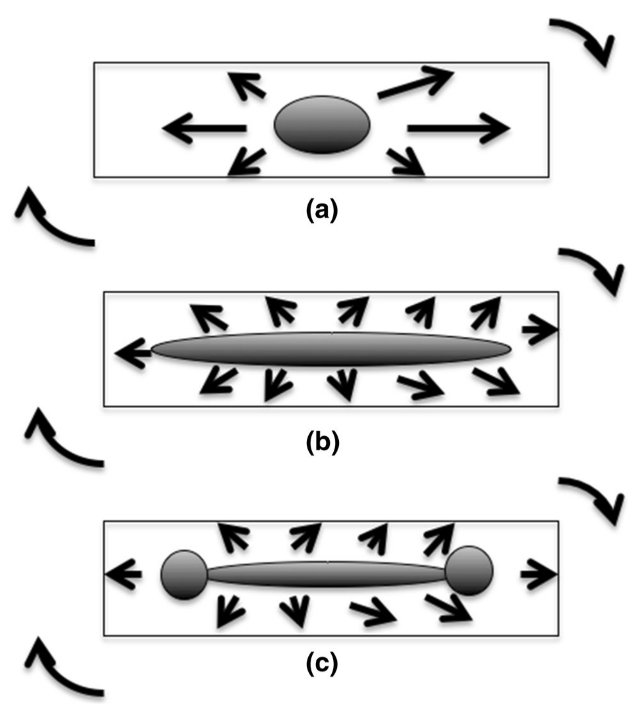

Fig. 5 Viewing a glass slide from above. The three plates *a*, *b*, *c* show the various ways of pouring the liquid on the glass slide to coat it evenly on a spin coater

The photoresist-coated wafer is an emergent whose final outcome is, at any given time, never guaranteed. The spin coating process involves a considerable amount of risk pertaining to the final outcome. Another important aspect to be gleaned from the process of spin coating is the nature of knowing and acting that is distributed between the individual, spin coater and the material. The spin coater should not be considered an instrument that produces finished products; rather, in the process of spin coating, given the workability of the materials at hand, the researcher had to learn the manner in which to use the spin coater in order to produce the optimal results.

After the spin coater is used to successfully coat the silicon wafer, the photomask is placed on the wafer and the UV light is applied. The UV light exposure system is also complicated and involves an understanding of the precise amounts of required radiation. In the fluidics laboratory where this study was conducted, a sign posted on the wall next to the UV exposure system cautions the users to be careful and asks them to get in touch with senior graduate students in order to learn operating the machine before using it directly.

Controlling the precise amount of UV exposure is essential for developing the "master mold." This involves setting up the precise voltage and current for the lamp intensity as well as the exposure time. There exists a calculated time for the exposure depending on the materials and the technical specifications of the machine. In a melange of appropriate combinations of dials and knobs, the researchers set the optimal conditions for exposure enabling the photoresist coated to be UV exposed for the required time. Overexposure or underexposure may damage the silicon wafer or render it unusable. In one case of underdevelopment, the boundaries of the channels in the master mold did not develop properly. This condition rendered the entire silicon wafer unusable. Silicon wafers and the materials required to etch it are expensive; therefore, researchers try to ensure that the wafers are not wasted. Thus, along with other factors, cost of the materials adds to the amount of risk involved in the fabrication process.

Further, the UV exposure system can be used to develop molds with multiple layers. Multiple layer development presents additional challenges. After the photoresist has been exposed, the unused portions are dissolved by a photoresist developer. The photoresist developer does not dissolve those areas that have been exposed to UV light as they become insoluble. Once the unused photoresist is dissolved, the silicon wafer is now ready to be used as a master mold. Typically, depending on the size of the LOC, in each master mold, five or six devices are etched. Based on the technical design, if required, master molds can be developed in layers. However, this particular laboratory focused on a single-layered device development. More layers would require a complex process and would add to the risk involved in getting the desired product. As already described before, the entire process is pervaded by the delicate balance of materials and workmanship along with a persistent ambiguity about the final outcome. The outcomes are not predetermined but emerge; the researcher in the capacity of a skilled workman, or craftsman, ensures that the materials are made into a working device. The creation of a master mold serves as the basis for future devices, and hence, the researcher carefully inspects the surface of the master mold to ensure that there are no discrepancies and faults in the layout. Once the master mold undergoes this visual inspection and is deemed workable, it is then used for creating the device.

2.5.3 *Molding*

The process of device creation, from the master mold, consists of three subprocesses: first, creating a PDMS mold from the master mold, second, creating the entry points for fluids in the PDMS and third, bonding the PDMS to the glass slide and thus producing the device. The first step in creating PDMS mold involves the recognition that the master mold will serve for the production of different PDMS materials; i.e., the PDMS should not remain stuck to the surface of the master mold in the process of demolding. Therefore, the surface of the master mold is coated with a silanization agent. A silanization agent makes the surface of the silicon wafer passive and later allows for the easy removal of the PDMS substrate, thus making it easy for the researcher to later remove the PDMS. However, the silanizing agent, trimethylchlorosilane (TMCS), is highly corrosive and thus is handled with extreme caution. In order to conduct silanization, a few drops of TMCS are placed in a glass petri dish along with the master mold into a vacuum chamber for designated amount of time. The vacuum allows the TMCS to evaporate and coat the silicon wafer.

The process of creation of the PDMS substrate is best understood as transformations of materials from a raw form to a finished form. The PDMS used in the process begins in the form of a PDMS base which is mixed with a catalyst in the ratio 10:1. Then this mixture is made homogeneous using a mechanical mixer. The mixing process may introduce air bubbles that can be later removed by degassing. Once the PDMS becomes bubble free, it is poured on the master mold. In order to achieve this, the master mold is placed in an aluminum casing and then the PDMS liquid is pored over it. Before poring the PDMS, both the aluminum foil and silicon wafer are cleared by a blast of high-pressurized air to ensure that no dust particles are present on the surface. Once cleared, the PDMS is poured into the mold.

Further, it is ensured that air bubbles do not remain in the PDMS, as air bubbles cause devices to be formed incorrectly. Once air bubbles are cleared, the wafer and aluminum sheet are placed on a flat oven for about 1 h to solidify the PDMS. The temperature of the oven is around 80–90 °C. Once this curing process takes place, the PDMS becomes stable. The transformation of PDMS started from the form of a fluid base and ended as a elastic solid after being baked for an hour on the hot plate.

Once the PDMS solidifies, it acts like a hardened piece of jello, retaining elasticity, but at the same time providing resistance. The researcher removes the solid PDMS from the wafer by cutting the PDMS on the sides in order to ensure that the molds are not destroyed (Fig. 6). Next, the PDMS is slowly peeled from the wafer and covered with a sheet of extremely thin transparent plastic wrap. The plastic ensures that the exposed surface that will be later stuck to the glass slide is not in contact with the dust. As mentioned before, dust is anathema for LOC researchers. Once plastic wrap is in place, the researcher proceeds to cut out the extra pieces and the devices that were obtained from one mold. Placing the plastic wrap on the PDMS has another effect; it makes the entire surface translucent. Thus to make appropriate cuts, the researcher often brings the PDMS close to a light to see the details clearly before proceeding with the cuts.

Cutting the molded PDMS into separate devices is a precarious and delicate process. As mentioned before, the PDMS acts like a hardened piece of jello and thus poses a resistance to the knife. Due to the resistance that the PDMS offers, the cuts often end up deviating from the intended case. In actuality, the deviated cuts are the norm rather than the exception. To counter this, the researchers use different approaches. Some use a sawing motion to slowly cut through the PDMS very slowly, whereas others mimic a chopping board. The ones mimicking a chopping board place the edge of the knife on the extreme end, extending their finger to make the end as a fulcrum point and then use the other hand to hold the PDMS in place. Then they proceed to "chop" the PDMS. In both the cases, the researchers adopt the particular techniques because it "feels right." However, a mere adoption of technique does not guarantee any success. Both the techniques require complete mastery in making precision cuts. The advanced researchers who have spent considerable time in laboratory work are often experts in this task. Novices find it difficult to master cutting techniques in order to produce straight cuts. However, despite the improper cutting, as long as the basic circuitry of the tubules in the device is not damaged, the device still remains functional.

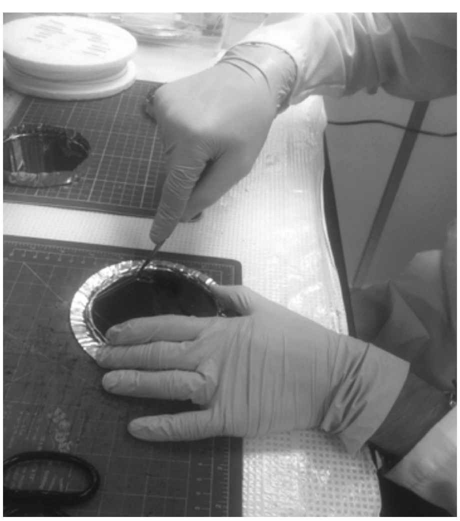

Fig. 6 Cutting the PDMS using a sharp knife to remove it from the mold. The knife is used at the edges to ensure that the mold is not destroyed. The freed PDMS will subsequently be sliced into smaller pieces

The next step involves making holes in the PDMS molds in order to allow for entry of fluids. Making holes is another process that requires a particular type of skill that the researchers learn through experience. Typically, researchers find it amenable to make the holes by hand using a syringe head of a particular gauge. The gauge size of the particular syringe head is comparable to the size of the microcapillary tubes that will be later used in device testing. The punching of these holes requires extreme care. If done quickly and with unequal force, the surface of entry will crack. A second problem is due to the application of unequal force resulting in abrasion of the sidewalls of the hole. The material dislodged by the abrasion of this sidewall ends up being forced into the channels by the inflow of fluid, resulting in clogging. Typically, a mechanical hole-punching machine is often used for this step of punching. However, the researchers showed a preference for manual punching using the above described metal needle, thus displaying an important dimension of workmanship.

Once holes are punched, the PDMS is ready to be connected to the glass slide for completing the device. In order to complete this final step, a glass slide is taken and spin coated to form an extremely thin layer of PDMS. The researchers then bond the coated glass slide with PDMS chips. The process of boding is quite delicate. Hardened PDMS has a non-reactive surface. In order to bond it very carefully with the glass slide, its surface has to be made reactive. This is done by exposing the PDMS to oxygen plasma under vacuum conditions. Two or three drops of a silanizing agent are placed in a petri dish along with the glass slide and PDMS for roughly around 7–8 min. The oxygen plasma makes the PDMS surface reactive. Once the PDMS has been exposed to oxygen plasma, it needs to be stuck to the glass slide immediately. This process requires dexterity and is extremely time-critical. Further, PDMS and the glass slide need to be properly aligned so that the device is functioning properly. However, the result of alignment and bonding cannot be immediately gauged. It is revealed in the process of testing the chip. During misalignment and bonding, sometimes chips show aberrations that are difficult to correct, hence, they have to be discarded. Considering the inherent ambiguity of the process adds to the measure of risk in LOC device fabrication.

One major challenge that the researcher faces in the process of bonding is the change in the properties of materials at hand. In its inert state, the PDMS is not bondable to the glass substrate. However, once exposed to oxygen plasma, the bonding can take place. The exposure of the PDMS to oxygen plasma is an extremely sensitive process. On the one hand, a too short exposure period will not create the proper surface; i.e., the silanol (SiOH) sites created on the PDMS surface will not be enough to create a strong bond. On the other hand, in case of over exposure, the SiOH sites will be in abundance resulting in a non-bonding silica layer. This fine tuning of the bonding process is rife with uncertainty. To manage the bonding process, some researchers have improvised techniques. One of them counted from one to eight in a paced manner for the time that PDMS is exposed to the silanol in the plasma chamber, whereas another counted quickly from one to 10. In terms of a consistent time measurement, roughly 7–8 s was noted. Both the above-mentioned researchers roughly used the same time for their idiosyncratic counting. After the exposure to plasma oxygen, the materials are taken out. The researcher using a perceptual-haptic judgment quickly stuck them together.

Making the LOC device in the laboratory is an extremely critical task, and successful outcomes are not always guaranteed. The device can easily get damaged, and the efforts behind the activity outlined above can easily be wasted due to the PDMS not being properly bonded. In one case, one researcher made about 10 devices in a day. Finally, after the PDMS bonding process, he found that two devices did not have properly formed channels: One device had a glass with a crack, which got exacerbated after the baking process, and two other devices were not bonded properly in the middle thus presenting a fluid accumulation in the device. The failure of these last two devices came only to be known once the device was tested the next day. In short, out of the 10 devices, only five worked. The ones that worked also later posed problems with debris stuck in the parts of the tubules of the device. It is not surprising that the device fabrication in the laboratory entails a considerable amount of risk of failure.

Once the PDMS and glass slide are bonded, researchers place them on the hot plate for further baking. The baking process takes place in two stages. First, the device is placed on a lower temperature of 65 °C. Later it is placed on a higher temperature of 95 °C. This is done in order to avoid heat stresses in the material. The device when exposed to high temperature may be heated unevenly on the bottom and topmost layers. The layer in contact with the heating plate will have a higher temperature, whereas the layer exposed to air will have a lower temperature. This will cause a heat gradient and uneven expansion of the device introducing unwanted thermal stress. Therefore, the device is heated at a lower temperature and then at a higher one. In order to cut the turn around time of research, some researchers conduct the entire device fabrication in the late afternoons and early evenings. Thus, having left the device at a lower temperature for a few hours, the researchers transfer it to the hot plate with a higher temperature and leave it for baking overnight. These devices are ready for testing next morning (Fig. 7).

2.6 Testing

After the device has been created, to ensure the fabrication procedure was successful, the researcher takes the role of an analyst. Earlier, the researcher was acting as a skilled craftsman involved in fabricating the chips. In contrast, in the testing phase, the researcher is involved in analyzing the fabricated chips (Fig. 8). Once the device is ensured to function properly, the researchers collect data based on their individual research projects. In this testing phase, along with the change in the researcher's role, other changes also occur at the same time. For example, during the fabrication process, researchers tried to avoid dust from the materials; in contrast, in the testing phase, the researchers tried to remove the debris from the tubing of the LOC. Also, there is change in instruments in the testing phase. Three main instruments are involved in the testing process—pressure controller, microscope and computer (software).

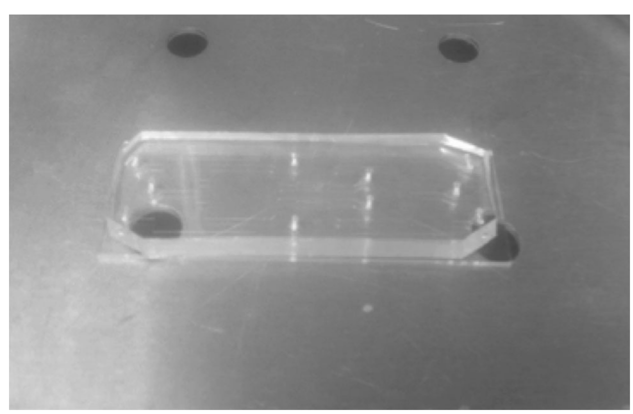

Fig. 7 Completed LOC device. The punched holes are evident in the figure. The circuitry of tubules is difficult to view unless placed at an appropriate angle toward the light

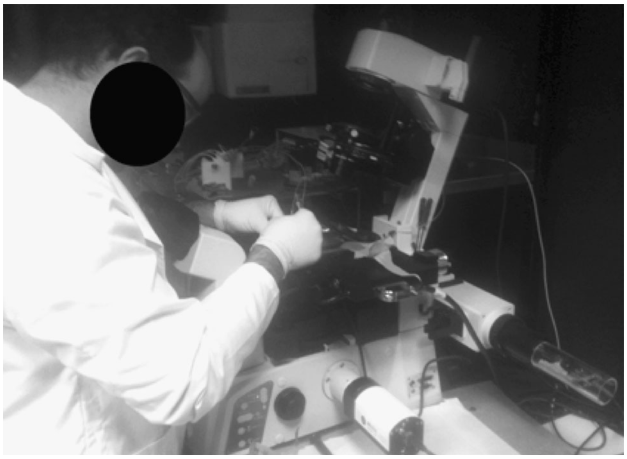

Fig. 8 Researcher setting up equipment for testing. The LOC is placed under the microscope that is connected to a computer. The details of the LOC device can be viewed on a computer

In the testing phase, the microscope and the camera attached to it are turned on in order to gather data. Based on the requirements of researchers, the camera recording rate and other parameters are set. Both the camera and the pressure pump are controlled by computer software. The software controlling the pressure pump is generally provided by the company that had manufactured the device. At the same time, the research laboratory in which the study was conducted used the software, Laboratory Virtual Instrument Engineering Workbench (LabVIEW). LabVIEW is a systems design and development software environment that is used in areas of data acquisition, instrument control and embedded systems design, among others. Along with the interfaces for data acquisition, microscopes also play a major role in LOC and nanotechnology in general. Microscope software provides image and video acquisition characteristics that are important for conducting research. In general, the use of instruments and flow pumps in LOC technology also requires an understanding for operating the equipment successfully, gathering appropriate data robustly and analyzing data creatively to make analytical discoveries.

The computer software, LabVIEW, is connected to the pressure controller. The pressure controller is used to modulate the flow characteristics of the liquids circulating through the LOC device. The flow from the pressure controller to the device depends on the length and diameter of the tube connecting the LOC and the relative height of the components. For this reason, the researchers use precise lengths of tubes and have the LOC device placed at fixed level, under the microscope. The tubes must be placed in a manner such that a constant flow is maintained through the device. In short, the LOC device should act like a component in a flow circuit. Typically, the lengths of the tubes are minimized to ensure stability of the flow. Also, an outlet tubing is provided to collect any flow that spills out of the device. In general, this waste outlet has to be placed at a lower pressure relative to the inlet. Since there is no suction placed at the outlet, the inlet pressure should be maintained higher than the outlet.

The choice of fluids in the channel depends on the purpose for which the device is designed. For example, two immiscible liquids could be used such that it allows for one liquid to be regulated as drops while the other liquid fills up the flow chamber between the drops. Many other combinations of fluids can be used. Moreover, depending on the application, the fluid flow can also be regulated by applying electromagnetic fields. The fluids are generally placed in bottles connected to the pressure controller.

As mentioned before, the pressure controller regulates the pressure in the device. Researchers observe caution while increasing the pressure. Excessive pressure in the tube leads to the rupture of the device. Further, excessive flow, in the beginning of the testing, pushes the debris into difficult corners of the tubing, making it extremely difficult to dislodge. Therefore, fine-grained control of the flow characteristics becomes an imperative for data acquisition in LOC research settings. The pressure controller requires a period of stabilization; therefore, it is generally turned on for 10–15 min before recording any measurements. In the first step of testing the chip, the chip is connected to the pressure controller and started with low values of flow rates. Later these flow rates are gradually increased to reach the desired experimental parameters.

Testing is the stage when the results of workmanship are finally revealed. During inspections, many devices show that the bonding was not properly done or debris remains in the channels. Sometimes, reversing the flow allows for dislodging debris stuck at extreme corners; this strategy, however, may not be successful all the time. In order to remove the debris, researchers sometimes increase the flow pressure; however, this may also cause damage to the device. In some cases, devices may rupture due to increased pressure (Fig. 9). Another problem, related to debris that often occurs in the device, is due to materials loosening from the wall where the holes were punched in the PDMS. When the fluid flow begins, this debris gets loosened and clogs the inlet of the device. Thus, the results of workmanship involved in punching holes are only revealed at the end of the testing stage.

Debris, from the viewpoint of the researcher, is an entity that has to be removed from the LOC channels. However, notwithstanding its size, a minor speck invisible to the naked eye often shapes the researcher's workday considerably (Fig. 10). For example, typically, once the debris is removed, the system needs to be stabilized before readings can be taken. Not surprisingly, the researcher tries to

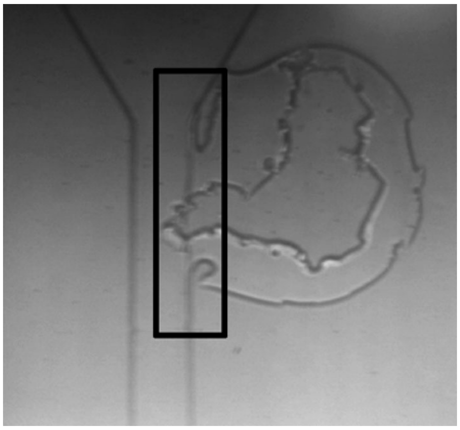

Fig. 9 Magnified image of LOC circuitry. The *highlighted* part of the figure shows that excessive pressure for clearing the debris caused a rupture in the wall of the tubes. This particular device had to be discarded

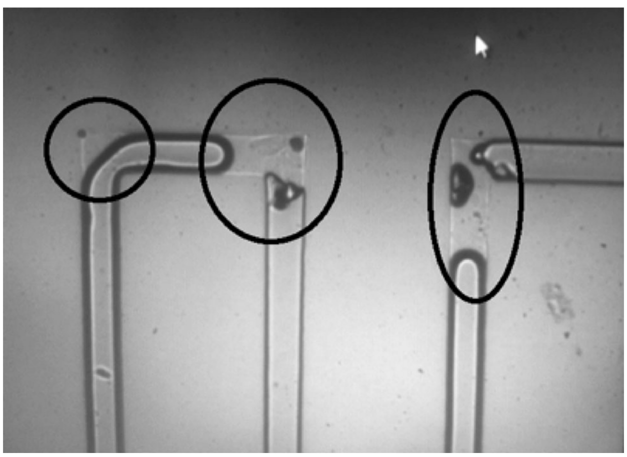

Fig. 10 Magnified image of LOC circuitry. Debris (*circled*) stuck to the walls of the tubes of the LOC device. After considerable number of attempts, the researcher found it difficult to remove the debris and therefore discarded the device

maximize the number of readings. Thus, a session which typically started early in the morning would sometimes take about an hour or more for the experiment to be simply setup and running. Once the system is set up, one specific researcher had a habit of taking continuous recordings with half an hour lunch break in the afternoon. The second half and hour break was taken at five in the evening. Finally, the experiment was wrapped up at 10 at night. This particular researcher took intensive data recordings for 3 days. Even though experimental regimes of other researchers were not always this extreme, nonetheless, the debris of the channel was a key aspect that shaped the researchers' work routines. Notwithstanding the above-mentioned challenges, researchers are able to fabricate working LOC devices and also successfully gather data for their research projects.

3 Discussion

This study was conducted in university laboratory settings in order to study the fabrication and testing of LOC devices. The LOC devices in the current study were fabricated by soft lithography techniques. The ethnographic study was divided into two major phases—fabrication and testing. In the fabrication phase, the chemicals were used to form a master mold on a silicon wafer. This master mold was used to form inert PDMS blocks that were later bonded with glass slides to make the LOC device. After fabrication, these LOC devices were tested to ensure that they were functioning correctly.

Over the course of the study, three important aspects were highlighted. First, LOC device research considerably involved aspects of activity that can be labeled as *situated*, both during fabrication and testing. In fabrication as well as testing, the device emerges as a result of the itinerary of chemical reactions and orchestrated improvisations on part of the researcher. Second, the device fabrication entailed a considerable degree of workmanship on the part of the researcher while fabricating the chips. Workmanship refers to the degree of skill by which the device is made. Workmanship involves judgment, dexterity and care required to create the end product. As shown in the ethnography, even though the design of the device was conceptually correct, the fabrication posed several risks. Beginning with the creation of the master mold to the bonding of the PDMS to the glass slide, at each step there is a possibility for the fabrication process to go wrong. As a result, the task of the researcher involves exercising dexterity, judgment and care during the fabrication process. Related to this notion of workmanship, a second important aspect to be highlighted was the notion of "workability of materials." Workability refers to the ways in which the various materials could be manipulated. These three points are discussed below in greater detail.

3.1 LOC research as situated activity

In HFE, researchers from various schools of thought have emphasized that cognition and activity in situations is contextual and emerges as the situation unfolds (e.g., see, Hutchins 1995; Lave 1988; Lave and Wenger 1991; Suchman 2007; among others). Suchman (2007) addresses the notion of activity by highlighting that actions are primarily situated in nature; i.e., they have to be understood in "the context of particular, concrete circumstances" (p. 26). Suchman's emphasis on actions as situated lies in contrast to actions as characterized by plans. Typically, when activity is characterized in terms of plans, it is depicted in terms of the actors, their intentions and the possible steps to achieve the outcome. In contrast, from a situated activity perspective, plans as a *complete* characterization of activity are a myth. In any given case, there are multitudes of ambiguities and perplexities that individuals face during the course of action. The resultant improvised activity is shaped by innumerable aspects, ranging from the material to the social. Thus, activity from the situated perspective is best characterized as emergent. In this emergent view of activity, plans can be best described as representations of action. These plans are abstractions in form of possible imagined accounts of activity or retrospective constructions.

The distinction between plans and situated activity is also visible in the LOC device domain. The device creation is often described in terms of a sequence of actions (a plan, see Fig. 3) prescribed by a scientific recipe. However, the ethnographic study revealed that the actual activity was composed of a myriad of constraints and contingencies that had to be negotiated by the researcher in order to create the device. The notion of situatedness of activity, as compared to the initial plan, is strongly reflected in both the fabrication and the testing of the LOC device. At each instance in the development of the chip, researchers are faced with physical and cognitive[2] challenges that they solve in situ. The physical challenges related to the fabrication involve instances such as the processes of pouring PDMS, cutting the PDMS pieces, bonding the PDMS with the glass slide, among others. At each instance in the process, the outcome of the activity is not predetermined; the results are contingent on the process, and the outcome is emergent. In many cases, this emergent result is undesirable; i.e., the bonding of the glass slide and PDMS may not occur properly resulting in the device to be discarded. These decisions as well as many others made over the course of the process constantly reshape the researchers itinerary as they progress in their research agenda.

Along with the physical challenges in the fabrication stage, the cognitive challenges become paramount in the testing stage. During testing, the researcher has to take into account the various sites of debris and their effect on the overall chip. As mentioned before, removal of the debris depends on the site in which it occurs. In many cases, the debris cannot be completely removed. Therefore, the challenge of the researcher is to make decisions whether to retain the device based on project criteria or discard it. These questions related to debris as well as other challenges for the flow in the device constantly arise in the testing phase. Each of the answers requires not only a generalized understanding of the project but also a detailed understanding of the situation as it unfolds.

Situatedness of activity involves an improvisational view of the work domain under consideration. Even though the soft lithography process is substantially generic and standardized, its orchestration and use in every research scenarios require local construction of action and range of localized choices that the researcher is constantly involved in throughout the process. Along with these localized considerations that emerge in situ, attentional demands on part of the researcher are also present. The researchers' involvement requires concentrated attention during fabrication as well as the testing of devices. At every instance, the attentional demands modulate the cognitive as well as physical activity. In case of fabrication, the attention and physical activity go hand in hand to produce the device, whereas in case of testing the device, cognitive activity involves concentrated attention for identifying debris and the associated feasibility of the device for data collection. The dimensions related to the physical and cognitive activity along with the attentional demands required for the LOC device highlight the situated nature of nanotechnology research settings.

3.2 Workmanship of risk[3]

In this particular domain, along with the salient aspect of in situ construction of activity, a related aspect is the degree of workmanship involved in the fabrication. Even though researchers design their devices conceptually, based on the scientific concepts and equations, the device fabrication in the laboratory entails a considerable degree of workmanship. The difference between design and workmanship can be addressed in the following manner: "Design is what, for practical purposes, can be converged in words and by drawing: workmanship is what, for practical purposes, can not" (Pye 1968, p. 1). The difference between design and workmanship is similar to plans and situated actions (Sect. 3.1); workmanship is inherently performative. However, performative workmanship corresponds to a specific activity of making. Making as an activity involves fashioning of entities from materials, bringing them together in ways such that the resultant is a creative endeavor. Making is inherently improvisational and processional (Ingold 2011, 2013, Ch. 4). In the case of the LOC device at the end of the process of fabrication, the materials were fashioned into a working device. This

[2] The terms physical and cognitive have been separated here for the sake of saliency of depiction. In a few cases of chip fabrication, the "physical" aspects of activity are prominent, while in other cases of chip testing the "cognitive" aspects are salient. However, even though these distinctions are made, no ontological split is intended between these terms.

[3] The use of "risk" in "Workmanship of risk" is different from the classical meaning of risk to humans and organizations in HFE research. In the current study, risk refers to the risk in the outcome of products from the workmanship involved in making and testing of LOC devices.

transformation was brought about by the workmanship of the researcher. Workmanship involves a considerable role of dexterity on part of the researcher. Further, the risk of damage at any time in the process is a key aspect of making LOC using soft lithography techniques. Specifically, in the case of fabrication of LOC devices, the workmanship is labeled as the "workmanship of risk" (Pye 1968, p. 4). Therefore, the "workmanship of risk" involved in this case can be characterized as,

> […] any kind of technique or apparatus, in which the quality of the result is not predetermined, but depends on the judgement, dexterity and care which the maker exercises as he works. The essential idea is that the quality of the result is continually at risk during the process of making; and so I shall call this kind of workmanship 'The workmanship of risk': an uncouth phrase, but at least descriptive (Pye 1968, p. 4).

While workmanship is definitely a performative and situated activity, it forms a unique subclass of performance in which the actor produces an entity. Here the actor's judgment, dexterity and skill are to be emphasized. In the case of LOC devices, after making these devices a multitude of times, the researchers (qua workmen) had evolved their own strategies of addressing the materials. This involved application of certain amount of force while cutting, ways of punching holes in the PDMS, among others. These activities, definitely labeled as situated, also involved a certain amount of judgment, care and awareness of the self and the material with a view toward making and creating. Thus, while all chips were made by the situated activity involving the researchers, the researchers who had improved the quality of their workmanship were able to produce more number of working chips.

Typically, dexterity and workmanship are explored in the literature related to physical ergonomics. At times, workmanship is also synonymously used with craftsmanship and is relation to quality in products (e.g., Bhise 2011, Ch. 10; Yun et al. 2004, for craftsmanship in vehicles; Iwaro and Mwaro 2012, for relation between workmanship and quality; Colombini et al. 2012 for relation between ergonomics and craftsmanship). Dexterity, a core component of workmanship also appears in context of skilled manual activity related to HFE (e.g., Dianat et al. 2014). However, as the LOC research reveals, the physical and the cognitive together should be understood to provide a holistic picture of the work domain under consideration.

Workmanship, specifically involving risk, is observable throughout the fabrication process. The first step in the process of fabrication involved the etching of the silicon wafer to form the master mold. This process involves a high amount of risk. If the etching of the silicon wafer is not correctly done, then the master mold is faulty, resulting in improper devices. The etching process required considerable care on behalf of the researcher. The use of chemicals as well as exposure to UV light posed a considerable challenge. If the wafer was not treated with chemical properly or the exposure time was not correct, the master mold would not be formed correctly, subsequently leading to improperly formed devices.

Along with the challenges posed by the master mold, the liquid PDMS needed to be degassed in order to remove trapped air bubbles. During the pouring of the liquid PDMS in the mold, the researcher takes extreme care to pour the liquid slowly to avoid introducing new air bubbles in the liquid PDMS. The liquid PDMS has to be poured in manner such that it results in an even molding. Uneven molding makes the cutting of solid PDMS difficult; thus, it may later result in improper device functioning, due to uneven cutting or damaging of flow circuitry. All these various aspects related to the device add to the amount of risk involved in the fabrication process.

Another source of risk is the removal of the solid PDMS from the master mold. During this process, the PDMS is carefully removed and wrapped in plastic sheet to avoid dust. This PDMS is later sliced into individual pieces. The slicing of PDMS requires considerable skill. The PDMS acts like a hardened piece of jello and resists cutting. Thus, the researchers, based on their experience and awareness of their own dexterity levels, devised optimal ways in which to approach the task. Typically, LOC chips are not understood in terms of human dexterity and workmanship. However, this ethnographic research reveals that the bodily based tacit dimension of dexterity played a crucial role throughout the fabrication process. This bodily based knowing was difficult for the researchers to articulate. However, after observing the researchers for sometime, one of them invited the first author to get a first-hand feel of devising the chip. Cutting the PDMS to appropriate dimensions provided the first author with a key insight into the bodily based nonverbal processes in fabrication that were previously missing from the observations and discussions of the LOC design process.

Along with the slicing process, punching holes also required considerable skill as well as simultaneously posed a risk. As described earlier in the ethnography, if the holes are punched incorrectly, then the fluid flow in the device will be improper, adding to the risk of device failure. Another source of risk in the fabrication process is the bonding of PDMS and glass slide. In many instances, the bonding may not be proper, leading to the seepage of fluid out of the network of capillaries in the LOC device.

To summarize, the risk of damage at any time in the process is a key aspect of fabricating LOC using soft lithography techniques. Even though the design was conceptualized earlier, the process of device fabrication was not. The LOC device emerged as an end product of a long process in which the researcher was averting risk while exercising judgment, dexterity and care in various stages of device fabrication. Thus, the entire process of fabricating LOC devices using soft lithography process in the laboratory can be characterized as the “workmanship of risk” (Pye 1968, p. 4)

3.3 Workability of materials

Along with the dimension of the workmanship of risk, an interrelated idea is that of “workability of materials.” The workability of the materials refers to the properties of materials that allow researchers to manipulate them and bring them to desired form. Typically, this involves perceptual and haptic interactions with the materials. For example, in the fabrication process, PDMS is a made into a viscous liquid to be poured into the molds. The viscous PDMS affords certain properties that can be understood haptically by the researchers; i.e., the viscous PDMS has to be poured in a manner so as to avoid air bubbles. Further, the viscous PDMS has to be poured so as to provide an even coating on the wafer. For this reason, based on the viscosity, over a period of time, the researchers acquire a steady manner in which to pour the liquid PDMS into the mold. This pouring of the liquid PDMS in a proper manner is based on perceptual and haptic knowledge acquired through experience of working with PDMS.

Another example of the change in the workability of materials is observable when the PDMS becomes solid. In this form, the researcher uses a knife to cut the PDMS into strips. In comparison with the older liquid form, the new solid form required a different manner in which the researcher interacts with the materials, both haptically and perceptually. As it was previously discussed, PDMS has certain properties, physical, chemical, among others, making it amenable for fluidics research at the small scale. However, PDMS also presents properties that aid or hamper workability at a perceptual and haptic level. Thus, aspects of workability and workmanship in LOC fabrication mutually support each other. Further, these interrelated aspects should be viewed in terms of situated activity involved in the research settings. For HFE research, in order to study situated activity in research settings, along with the cognitive demands involved in conceptualizing LOC devices, HFE professionals should also note the workmanship involved in devising LOC technology in university laboratory settings. Attending to the situated activity, the workmanship of risk, and the workability of materials will allow for a complete understanding of the LOC settings for small-scale fluidics research.

4 Implications for HFE research

A major challenge for HFE research is the nature of domain of nanotechnology. Nanotechnology poses new challenges in terms of scale and the behavior of matter at very small scales. In terms of behavior of the matter, many phenomena are observed at the small scale that is not quite salient at the everyday scale of human knowing and acting. For example, quantum effects dominate properties of materials; surfaces of materials and interfaces between materials play a paramount role; many biological transport processes and exchange of matter exist at this scale, along with entities such as contaminants that are comparable to the micro-/nanoscale particles have a major effect on the functioning of materials/devices. Also, in the case of the LOC device, the debris caused problems in achieving a laminar fluid flow in the device. Along with matter, the challenge of scale includes acting on entities often beyond the scope of everyday vision. The researcher tries to connect the everyday scale of actions to the small scale of micro-/nanotechnology. The important aspect is to understand “how” these disparate scales are connected via the situated activity of researchers in particular contexts. In the context of the LOC device, the researchers relied on everyday vision to create the device and enhanced their vision (via microscope) for testing the device. Similarly, the task of creating the device was based on chemical processes and physical tasks of peeling, cutting, among others. Thus, primary implication for HFE research is to address these constraints and contingencies as they present themselves in everyday tasks related to nanotechnology. As HFE and laboratory research proliferate in nanotechnology, the various ways in which researchers from different fields address their work will become important. For HFE, a major challenge will be to address these multiple viewpoints and activities from the various instantiations of nanotechnology as work domain (e.g., nano-biosystems, nano-chemical systems, etc.) to provide a holistic understanding of small-scale technologies.

A related challenge is the aiding of laboratory research. Aiding research would be possible by supporting intellectual work, insights relating to discoveries, as well as supporting the regular laboratory work (for e.g., see Gould 1995 for the necessity for HFE to aid intellectual work). HFE professionals can provide support to both the above aspects of research. In the scenario of LOC device, the process of fabrication of the device can be improved in performance. As described above, devices fail regularly due to the risk involved in the process of fabrication. In this case, the challenge for the HFE professional is to provide training for the researcher to improve performance and reduce device failure (e.g., see Grossman and Salas 2011, for issues related to training). Thus, training would not only be providing a successful scientific outcome but also a human-centered outcome with improved productivity and reduction in wastage of material and resources.

Another manner in which research work can be supported is through the design of devices and software for aiding intellectual work. For example, in the LOC device domain, the researcher had to visually ascertain the debris-stuck areas. In this scenario, the challenge for HFE is to provide software that will allow for visual aids to help the researcher to enable discovery of such sites and thus reduce the time related to device testing (e.g., see Tory and Moller 2004 for human factors in scientific visualization; Kehrer and Hauser 2013 for a survey of scientific visualization). Further, the devices involved in the current testing phase are controlled by the software LabVIEW. LabVIEW is generic software in which researchers (also sometimes device vendors providing software) design their interfaces to enable the testing. The HFE professional can aid in intellectual work by providing customized interfaces for applications such as monitoring crucial variables for device testing. For example, in HFE, Ecological Interface Design (EID) has been successfully used for interfaces for process control systems (e.g., Burns and Hajdukiewicz 2004; Vicente 2002). Since testing devices involves monitoring of crucial variables, EID may provide renewed success at the smaller scale. The above implications are based on the research conducted at one nanotechnology setting; as more research will be conducted by HFE professionals in nanotechnology, myriad avenues and novel engagement ventures will, no doubt, arise.

The rationale for conducting research in university laboratories was that the universities are now considered as crucial actors in the innovation ecosystem. As studies on university laboratories proliferate, HFE members can contribute to the process of commercialization and technology transfer by aligning the research and development pathways for usable products. Explicit mechanisms for technology transfer and the role of the HFE professional in the innovation ecology have to be addressed in the future. Having the HFE professional as an important actor in the innovation ecology will enable a proactive stance on human-centered product development. The aim of HFE is to provide value to the society; by creating a niche in the innovation ecology, this goal can be accomplished. Ultimately, as mentioned above, good economics requires good ergonomics.

5 Conclusion

In the above description of LOC devices, the focus research area was fluidics at the small scale. An ethnographic study was conducted in a university laboratory in a small-scale fluidics laboratory at the University of Waterloo, Canada. In this study, the steps of fabricating a LOC device from raw materials and testing it were presented. In particular, the steps involved a discussion of the situated nature of activity, risk involved in workmanship and the workability of the materials. It was highlighted that along with the scientific character underlying the LOC device, it can be best characterized as an emergent aspect of situated activity, workmanship of risk and workability of the materials. During the fabrication and testing of the chip, the researchers had to face considerable challenges that they solved in situ. These challenges ranged from the cognitive to the physical aspects of LOC device fabrication and testing. These situated aspects of the device creation involved a considerable measure of skill, dexterity and risk of workmanship that was supported by the workability of the materials as they changed throughout the course of the fabrication process. The ethnography also unveiled a manner of device creation that complements the traditional science-based view of LOC devices. This nature of the device creation involving human activity is amenable to the research traditions already underway in HFE. It should also be noted that the focus on fluidics is just one research area in the study of LOC devices. Other areas include micro-/nanoelectronics, as well as applications ranging from health care to biodefense. For a complete understanding of LOC device design in research settings, these other research areas have to be addressed for developing sustained concepts linking LOC research in nanotechnology and HFE. More broadly, studies are needed in various dimensions of nanotechnology for systematically addressing it as a work domain in HFE research. Further, research is also needed for linking the output of university research settings to the industry for viable and successful commercialization. In the future, it is expected that HFE professionals will play a greater role in the innovation scheme of nanotechnology, linking universities, industry and society for a sustainable future.

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