Direct roll transfer of silicon nanoribbons onto polyimide substrates accomplished in one step

The manufacture of electronic devices and circuits with flexible form factors and high performance is an area of increasing importance. Even though transfer printing has shown good potential for the development of such materials, it remains a challenge to have complete control over printing parameters and interface properties, which affects yield and reproducibility. In a recent issue of *npj Flexible Electronics* (<https://doi.org/10.1038/s41528-021-00116-w>), researchers from the University of Glasgow reported a simple, cost-effective, yet robust direct roll transfer method printing technique and employed it to develop nanoribbons-based field-effect transistors (NRFETs).

“The key merit of this work is the direct roll transfer printing process itself. Unlike conventional transfer printing, it is a single-step process, and it does not require any elastomeric stamp to print nanoribbons,” Ravinder Dahiya, who leads the Bendable Electronics & Sensing Technologies Group at the University of Glasgow, told *MRS Bulletin*. The Si NRs are first fabricated on commercial silicon-on-insulator (SOI) wafers using a conventional

nanofabrication process that produces horizontal arrays of NRs. “Silicon offers high mobility, which is critical to obtain high-performance electronics. In the NR form, it is easy to print on flexible substrates. Hence, Si NR is chosen to obtain high-performance flexible electronics. However, our method can also be used for other inorganic structures,” Dahiya says.

During the direct roll printing process, the SOI wafer with Si NRs, also known as the donor substrate, is brought into direct physical contact with the semi-cured polyimide (PI) thin film over the receiver substrate as seen in the **Figure**. After the direct transfer of the nanoribbons, annealing of the coated PI—which acts as an adhesive—is required. Low-temperature steps were carried out to realize devices on flexible receiver substrates.

Since the annealing process could be limited by the type of substrate, the researchers demonstrated the methodology on a variety of flexible receiver substrates such as metal foils (Al, Cu, and Mg) and polymers (Kapton, sheet, poly(ethylene)terephthalate, and PI). Morphological analysis was performed using scanning electron microscopy (SEM), optical microscopy, and atomic force microscopy (AFM) to evaluate the quality of direct roll printed NRs. SEM images showed how the arrays of Si NRs with perfect registration (precise alignment) were transferred over the PI substrate

and the registration values perfectly matched with the NRs on the donor wafer.

The reliability and robustness were also evaluated by the transfer yield of NRs from the donor to receiver substrate by studying the dependency on the applied force on transfer yield. The

transfer yield increased with increasing applied force and reached 95% with a contact force of 12 N.

The surface quality of the transferred Si NRs on the receiving substrate (PI) was investigated by AFM. The surface topography was found to be free from polymer residues/contamination, which is a common drawback in conventional transfer printing.

The printed Si NRs were used to fabricate top-gated field-effect transistors (FETs) on the flexible PI substrate. “The printed transistors consistently show high performance: high on-state current (I_{on}) > 1 mA, high mobility (μ_{eff}) > 600 cm²/V·s, high on/off ratio (I_{on}/I_{off}) of around 10⁶, and low hysteresis (<0.4 V),” Dahiya explained in email correspondence. The threshold voltage (V_{th}) remained constant with applied voltage, indicating high stability charge transport behavior under different voltages. Also, the extracted mobility compares well with most state-of-the-art Si NR-based devices previously reported.

The mechanical robustness and device stability of the NRFETs were evaluated under different bending conditions. Slight variations in I_{on} were observed while other devices parameters, such as V_{th} , remained unchanged. Tensile bending strain led to a slight increase in the drain current (I_{DS}) whereas compressive bending led to a decrease in the I_{DS} . The robustness of the device was studied during 100 bending cycles and results showed that I_{on} remained nearly stable with repeated bending.

Dahiya and co-workers are convinced that this approach “will resolve the issues related to huge waste that is generated by the conventional micro/nanofabrication process and potentially lead to a sustainable solution for electronic waste too. It will enable the transition from conventional micro/nanofabrication to fully print-electronic systems without sacrificing the transformative power of conventional electronics. Our study will play a crucial role as we are now capable to show the first demonstration of high-performance CMOS circuits.”

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Direct roll printing of nanoribbons from donor silicon-on-insulator (SOI) to semi-cured polyimide (PI) substrate.