Chapter 17
CIGS-Based Flexible Solar Cells

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Abstract This chapter reports the progress on the fabrication of thin film CIGS-based solar cells by means of the low temperature pulsed electron deposition technique. The innovative and multidisciplinary approach aims to solve the main issues preventing a possible industrial scale up of the process, i.e. the need of a fast, reliable and automated process, suitable for both static and dynamic deposition of CIGS solar cells on flexible substrates. The final goal is to open new opportunities, particularly in the emerging field of the building-integrated photovoltaic.

17.1 Scientific and Industrial Motivations

The global economic situation of the renewable energies and the photovoltaic (PV) market is in continuous evolution. The economic analysis goes beyond the scope of this work, but the analysts agree that renewable sources will gradually but unavoidably fill the gap between energy demand and supply, due to the decreasing availability of fossil fuels. A complete transition between fossil fuels-based technology and the mix of different renewable energies will be accomplished by 2050 [1].

During the Convention on Climate Change held in Paris (COP21, 2015), the world's policy leaders decided to limit the global warming below 2 °C and to strive eventually to 1.5 °C. These targets are very ambitious but this optimistic view is justified by the awareness that there are cost-effective technical solutions already

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available today and further efforts must be done in this direction to match the Paris goals. Solar power plays a major role in this effort.

From the industrial point of view, the penetration of PV in the electricity market has rapidly increased thanks to the introduction of incentives in several countries. In Italy the PV fraction at peak time has already passed the 20% and it is still growing despite of the cut of the feed-in-tariff scheme. The cost of own-produced PV electricity for the Italian domestic user is already well lower than the average price of grid electricity (grid parity) even in absence of incentives [2].

The availability of new PV products specifically designed for the building integration will cause a further significant reduction of the costs associated with the design and the installation of domestic PV systems. Given that domestic, commercial and public buildings together account for more than 50% of the overall electricity consumption in Italy, the emerging field of the building/product integrated photovoltaic (BIPV & PIPV) in combination with the diffusion of smart grids, surely will have a major impact on the overall PV diffusion.

Thin film solar cell (TFSC) is the most suitable technology for BIPV applications and Cu(In,Ga)Se_2 (CIGS) seems to be the most promising candidate for its good compromise between conversion efficiency, aesthetics, stability and possibility to be grown on different substrates, including flexible ones.

Being a complex material, one of the main limitations is represented by its cost, due to the expensive and complicated processes to grow it. Several industries and research centres worldwide are trying to develop production processes alternative to the commonly used multi-stage co-evaporation/co-sputtering followed by the selenization. In the search for simple and cost effective methods for the deposition of TFSC, a new process for the deposition of TFSC has been recently developed at IMEM-CNR in Parma, based on the Pulsed Electron Deposition (PED). This technique, already demonstrated the possibility to realize, on laboratory scale, CIGS-based TFSC with high PV conversion efficiency using a very cheap and simple method [3]. PED has important advantages, such as low installation and running costs and the capability to transfer of complex materials from a bulky target to the growing film in a single-stage process, without any post growth treatment. Even more important, PED allows the growth of high-quality CIGS at low temperature (the technique is also known as LT-PED), enabling the use of a large number of substrates, including polymeric and thermo-labile ones. Therefore, PED is an effective method to grow complex materials and to realize unconventional devices, such as flexible solar cells.

This chapter reports the achievements to solve specific issues that hinder the industrial scale-up of this novel process, ambitiously aiming to transfer the PED technology to a (pre)industrial level and to re-create an Italian industry in the strategic PV sector. To do this, the following issues must be addressed:

- Adapt the conventional PED for the deposition on flexible substrates.
- Provide a better control of the deposition rate via automation of the film growth
- Increase the deposition rate of the PED process.
- Realize a prototype system for the continuous (roll-to-roll) deposition of flexible solar cells.

The ultimate goal is the fabrication of a PED system prototype to deposit flexible CIGS-based solar cells, both in a *static* and in a *dynamic* process.

17.2 State of the Art

Commercially available TFSC suitable for BIPV applications are made of: cadmium telluride (CdTe), amorphous or microcrystalline silicon (a-Si) or CIGS.

CdTe has been the first thin film technology to emerge as a cost competitive alternative to crystalline silicon. The PV efficiency reached recently 22.1% in early 2016, 16.4% on commercial modules [4].

The American company First Solar is currently among the top 5 PV manufacturers although their products based on large glass substrates still do not differ significantly from the standard Si flat panels. Furthermore, CdTe is a controversial material for the environmental risks associated with both production process and end-of-life disposal of the PV modules. As a matter of facts, First Solar has been primarily responsible of the TFSC price drop since 2006.

As far as a-Si concerns, Swiss EPFL's Institute of Microengineering reached a remarkable 10.7% efficiency single-junction microcrystalline silicon solar cell [5], beyond the previous record of 10.1% held by the Japanese company Kaneka Corporation since 1998. However, the efficiency seems to be still too low for a significant market share of a-Si based TFSCs.

CIGS-based solar panels are commercial products. However, despite CIGS solar cells have reached 22.6% efficiency on the lab scale [6], the industrial scale-up of this technology is very challenging. Basically, only the Japanese company Solar Frontier has a significant CIGS volume production, while several companies in the last years (e.g. Solibro, MiaSolé, Solyndra, Avancis, Bosch, Global Solar Energy, Soltecture, Nanosolar, AQT, HelioVolt, Ascent Solar, SoloPower, TSMC, Manz, NuvoSun, Siva Power, etc.) have suffered serious financial problems. Flisom, a spin-off company of EMPA (the Swiss Material Science and Technology research centre), is specifically working on flexible CIGS, but it is not on the market, yet.

The main reasons are the complexity of the production processes and the cost of the production lines. Different deposition processes have been developed for the production of CIGS solar cells [7]. Among them, thermal co-evaporation [8], sputtering/selenization [9] and electrodeposition [10] are considered as the best options for industrial development, even though they are still characterized by severe limitations. Multi-stage co-evaporation, the so-called three stage process, holding the lab-scale PV record efficiencies [6, 11], is not suitable for mass production because of its complexity and limited composition reproducibility in large manufacturing systems [12]. Sputtering of metal precursors alloy followed by a post-growth selenization step seems to be more promising for industrial scale up. However, the selenization stage [13] has a strong environmental impact because of the use of highly toxic H_2Se gas. Moreover, the need of high temperature processing [14] makes both methods extremely costly, complex and time consuming.

In the last years, several single-stage processes based on sputtering [15] and co-evaporation have been proposed. The efficiencies reported for lab-scale cells are usually lower than 12.5% and the only exception is represented by an in-line co-evaporation process at a substrate temperature $T_{sub} = 550$ °C, able to achieve 18% efficiency [16].

The PED technique developed at IMEM-Parma is very efficient in reducing the deposition costs [3, 17]. CIGS-based thin film solar cells with 17% efficiencies by using a low-temperature single-stage PED process, have been recently reported [3] on a small area, resulting in a dramatic simplification of the deposition process compared to the conventional methods. It is remarkable to note that the active layers were deposited by PED at 270 °C, thus suggesting the possibility to use polymeric flexible substrates that usually do not stand high temperatures; this is extremely appealing for the BIPV/PIPV growing market.

PED is based on high-power electron-beam ablation of a bulk material (target) having the desired composition and stoichiometry. Electron beam pulses of about 100 ns dissipate a power density in the order of 10^8 W/cm^2 within a depth of $\cong 1$ μm of the target surface. This leads to the rapid, non-equilibrium evaporation of all the elemental components of the target, regardless the single element melting point or vapour pressure and the formation of a could of ions (plasma plume) with a large average kinetic energy, as schematically shown in Fig. 17.1. Therefore, the deposition of good quality CIGS films occurs at a much lower substrate temperature compared to sputtering or single-stage co-evaporation.

Although the reported result is extremely promising on a laboratory level, the technique still suffers some limitations that prevent a real industrial application of the CIGS-based solar cells grown by means of the PED technique; the goal is to fill this gap.

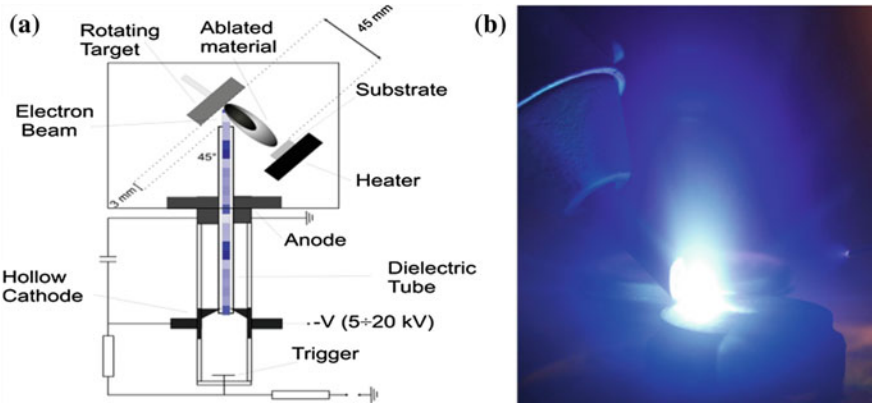

Fig. 17.1 Representation of the pulsed electron deposition (PED) technique: **a** schema, **b** in operation

17.3 Problem Identification and Proposed Approach

This section presents the different issues that must be addressed to enable the fabrication of CIGS-based TFSC by PED beyond the lab-scale area and on flexible substrates.

17.3.1 Improvement of CIGS Solar Cell Efficiency by Controlling the Substrate/Mo/CIGS Interfaces

A CIGS solar cell is a multilayer device where the interfaces significantly affect the performance. The typical structure is: substrate (glass, 1–3 mm)/back contact (Mo 1 μm by sputtering)/absorber (CIGS, 1.8 μm by PED)/buffer layer (CdS, 70 nm, by chemical solution)/window layer (transparent conductive oxides, TCO, ZnO-ZnO:Al, by sputtering).

The Mo/CIGS interface is identified as the critical interface to improve the electrical performance of the solar cell, in particular of flexible devices during the bending.

17.3.2 Selection of Flexible Substrates and Optimization of Substrate Holder

The selection of suitable flexible (polymeric) substrates is based on three parameters: (a) temperature resistance (up to 300 °C); (b) thermal expansion coefficient (TCE) and (c) stress stability. Their surface morphology has to be comparable to the glass (roughness ≈6 nm).

Kapton is chosen as benchmark for testing the Mo growth, being cheap and easily available. Other polymeric substrates, such as polyimide (PI) or polyethylene naphthalate (Teonex) from Dupont, perfluoroalkoxy alkanes (a copolymer of tetrafluoroethylene, PFA), fluorinated ethylene propylene (FEP) and ethylene tetrafluoroethylene (ETFE), provided by Saint-Gobain, were analysed in the temperature range 165–260 °C. Besides, metallic foil (stainless steel, SS 430B) and carbon fibres were also tested as possible substrates.

Obviously, the flexible substrate requires a tailored substrate holder.

17.3.3 Film Growth Automation

The film thickness and growth rate are the fundamental parameters to be monitored and controlled. The oscillating quartz microbalance, which is commonly used in physical vapour deposition (PVD) techniques, cannot be utilised with highly energetic pulsed beams. An alternative method, using an infrared (IR) pyrometer, can be used to measure the heat irradiated by the sample during the deposition. The

total radiated power per unit area, called the photon radiant emittance, is constant at constant temperatures (Stefan-Boltzmann law), but it is subjected to interference phenomena when irradiated from a thin film, leading to changes of the radiant emittance not depending on temperature. By analysing the emittance profile, the interference fringes due to the CIGS thickness variation appear, enabling the measurement of growing film thickness [18]. Once the film reaches the desired value, a dedicated software moves the substrate.

Optical Emission Spectroscopy (OES) has been employed to monitor in real time the composition of the PED plasma plume. OES is based on the detection of the optical emission (excitations and ionizations) occurring in the plasma. Since the plasma consists of the elements composing the targets, the absolute intensity of the emission peaks gives information on the ablation rate, while the ratio between emission peaks from different elements reveals the plasma stoichiometry. Both the ablation rate and the stoichiometry transfer depend on the PED acceleration voltage and the gas flow.

17.3.4 PED Source Current Stability

To achieve the physical *ablation* of the CIGS target, it is necessary to heat it suddenly, preventing the thermal *evaporation*. Being CIGS an incongruent melting material, the *slow* heating leads to the target melting, resulting in the deposition of unwanted phases. In short, this is the reason why PED is so efficient to deposit complex and incongruent melting materials such as CIGS.

The energy power (i.e. e-beam acceleration voltage multiplied by electron current) is the main parameter for controlling the mechanisms of PED ablation (congruent/incongruent evaporation, plume distribution and expansion range, stoichiometry transfer, adatom energy, particulate density, etc.) [19]. The e-beam acceleration is nominally the voltage needed to fully charge the capacitance connected with the hollow cathode and is set by the operator in commercial PED sources. The electron current depends on the combination of charge voltage, source geometry (tube length, cathode aperture), trigger type, gas type and pressure. While the former parameters are constant during the deposition, the gas pressure inside the source changes due to the warming of the cathode and the dielectric tube. The evaluation of the current drop induced by the change of the local pressure and the way to keep constant the energy power transferred to the target is essential for long time depositions. This measurement, not provided by the commercial PED system, can be made by using a contactless toroidal coils, called *Rogowski coils*, placed around the dielectric tube.

The variation in time of the discharge current of the pulsed current (pulse duration ~100 ns), generates a variation of magnetic flux inside the Rogowski coil, proportional to the variation of the discharge current in time. The automatic feedback of the discharge current measurement stabilizes the signal, by remotely controlling the flux-meter injecting the gas into the chamber.

17.3.5 Increase the PED Deposition Rate

The deposition rate in the PED technique depends on many factors, among which the electrical parameters of the source, the material to ablate and, above all, the pulse repetition rate. For CIGS, a typical deposition rate value is 0.25 nm/pulse over a 3 square-inch substrate (implying about 10′ to deposit 1.6 μm thick CIGS layer). This process must be much faster for a pre-industrial development.

The easiest approach would be to increase the pulse frequency; since a single pulse has a duration of only 100–200 ns, the maximum frequency could be much higher than 20 Hz, that is the maximum repetition rate provided by the only 2 companies commercializing the PED sources (Organic Spintronic, Italy and Neocera, USA). While a faster electronic could be in principle easily implemented, the main problem is the presence of the dielectric tube guiding the electron beam from the PED body that cannot stand higher frequency for the rapid heating, leading to the melting of the tube.

An innovative solution is to drive the electron beam using a supersonic gas beam, instead of a tube [20]. Further advantages of the tubeless solution, are: (i) easier process (the tubes are the only parts that require periodic cleaning and substitution), (ii) removal of geometrical constraints, and (iii) reduction of contaminants, typically silicon and carbon.

17.4 Developed Technologies, Methodologies and Tools

The main achievements to solve the problems identified in Sect. 17.3 are hereafter reported. The adopted solutions are selected on the basis of their feasibility rather than the scientific innovation, in view of a possible integration in a production line.

17.4.1 Optimization of Molybdenum Films on Flexible Substrates

Molybdenum (Mo) is generally used as back contact in TFSC to collect the photo-generated charges. While the deposition of Mo on rigid glass does not represent a major issue, the use of flexible substrates poses serious limitations to the solar cell performance. Mo films sputtered on flexible substrates are investigated by atomic force microscopy (AFM) and compared to the film grown on glass at room temperature (RT), as reference. Typically, films have a surface roughness of approx. 2 nm and composed of grains with an average diameter of 60 nm. The roughness parameter H [21], which describes how the film morphology changes in the plane, is approx. 0.3, indicating that films are quite smooth over large area.

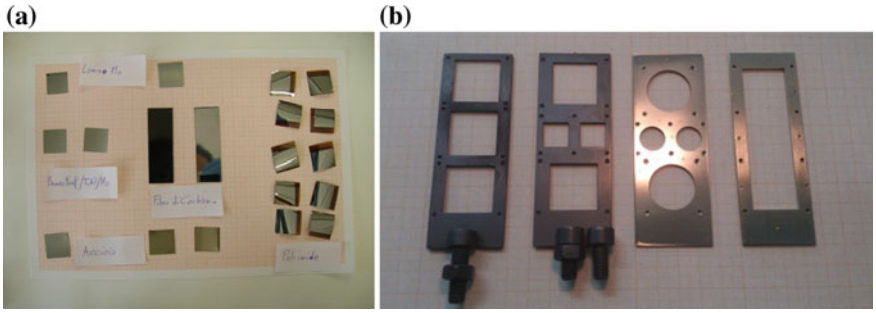

Fig. 17.2 **a** Different Mo coated flexible substrates and **b** sample holders suitable for CIGS deposition by PED

Mo films were firstly sputtered on kapton, by using the same experimental conditions used for glass (film thickness 500 nm, substrate temperature RT). Such films are rougher (≈6 nm) and composed of bigger grains with an average diameter of 160 nm. H isapprox. 0.04, indicating a *jagged* surface, in agreement to the roughness increases. In order to decrease it, kapton was heated at 120 °C during the deposition. Doing so, the surface roughness significantly decreases to approx 3 nm, but severe cracks appear in the film due to the permanent bending of the polymeric substrate generated by the heating. In order to remove such cracks, suitable sample holders for flexible substrates are designed, fabricated and successfully tested (Fig. 17.2). Other polymeric substrates (PFA, FEP, ETFE and PI) exhibiting smooth surfaces (roughness ranging from 0.5 to 4 nm) and temperatures resistance from 165 to 260 °C, were tested. Among them, preliminary results on adhesion and conductive properties of Mo films sputtered on FEP in the same experimental conditions (film thickness 500 nm, substrate kept at RT) indicate that it is a promising substrate for fabricating flexible CIGS-based TFSCs.

The exploitation of the Mo layer required the development of a radically new method for the substrate heating, based on the application of a DC electrical power directly through the Mo back contact of the cell, thus converting electrical energy into heat by Joule effect (Fig. 17.3). The very efficient heat transfer to the thin (<1 μm) Mo layer requires a low electrical power density (few W/cm^2) to achieve the required deposition temperature, that is much lower compared to the traditional resistor- or lamp-based external heaters. Joule-heated CIGS based TFSCs shows comparable or slightly better PV properties than conventional heaters [22].

17.4.2 Film Growth Automation

The real-time control of the CIGS film thickness is carried out by analysing the heat radiation emitted “in situ”. A pyrometer (model Marathon MM LT), located outside the chamber measures the IR radiative power emitted from the substrate

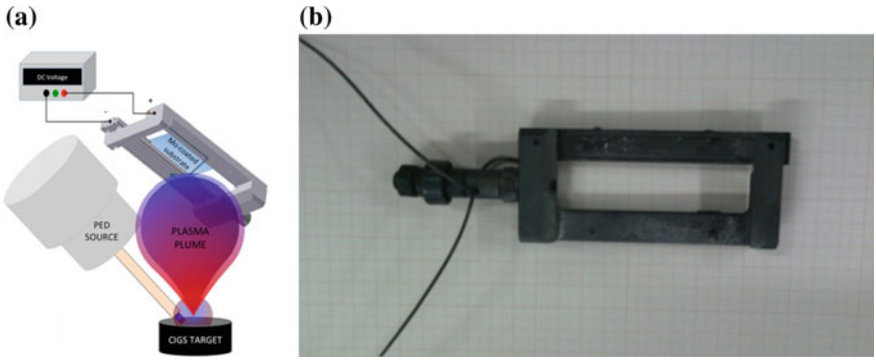

Fig. 17.3 Joule heated flexible substrates: **a** scheme and **b** sample holder

surface through an IR-transparent ZnSe viewport. A LabView software calculates the T = f(t) function, stopping automatically the deposition when the CIGS thickness achieves the desired pre-set value.

The temperature is acquired and filtered every 200 ms and the average temperature value is calculated every 5 points (1 s), limiting the signal noise. Both 1st and 2nd derivative of the T versus time function are instantaneously calculated. When the first inflection point (2nd derivative = 0) is detected, the average deposition rate and the expected time for maximum peak and deposition end are calculated. These calculations are repeated when the maximum (corresponding to a CIGS thickness = 1018 nm) and the second inflection point are reached. Finally, when the curve reaches the minimum (roughly corresponding to the desired final thickness = 2036 nm), the software shuts down the PED source, automatically stopping the deposition process.

The system is very precise and it has been installed in all the deposition chambers currently in use at IMEM-CNR equipped with PED.

The deposition rate is recorded by analysing the temperature versus time, as shown in Fig. 17.4. To further increase the sensitivity in the calculation of the deposition rate, a real-time evaluation of the PED parameters by OES is employed, using a Hamamatsu mini-spectrometer (250–800 nm range). Due to the pulsed nature of PED process, 20 subsequent spectra taken every 300 ms are averaged (every 6 s). The dependence of the OES spectrum on the acceleration voltage is shown in Fig. 17.5. By increasing the voltage, the intensity of the In peak at 325 nm, hence the deposition rate, reaches a maximum at 16 kV, then slowly decreases for higher voltages. The ratio between Ga (417 nm) and In peak becomes constant (0.5) at voltages greater than 12 kV, while the ratio between the Cu (521 nm) and In peaks saturates at 0.30 for values exceeding 14 kV. These trends confirm that an optimal stoichiometry transfer is achieved at voltages higher than 14 kV, while the maximum ablation rate occurs at 16 kV. During the deposition process, when a change in the OES spectrum and/or a variation in the deposition rate are detected, the PED parameters (voltage and gas flow) can be varied in order to recover the optimal conditions. It worth noting that the gas flow is an essential parameter for controlling both the ablation rate and the

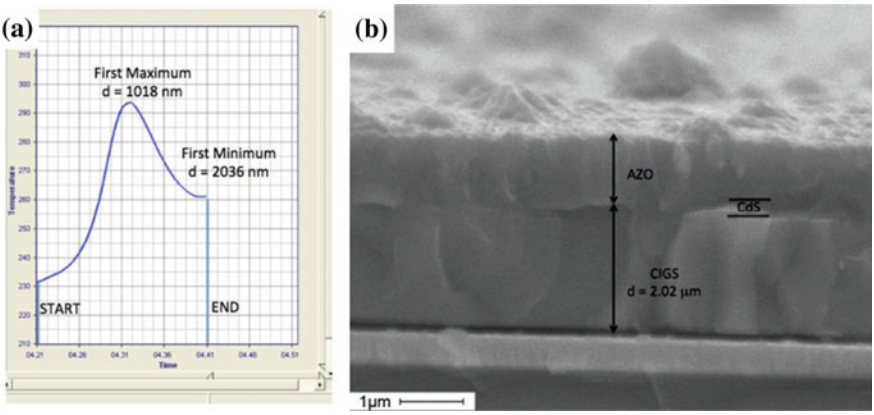

Fig. 17.4 **a** Substrate temperature as measured by the optical pyrometer during the deposition of 2 micron-thick CIGS by PED and **b** corresponding SEM cross-section of the final cell

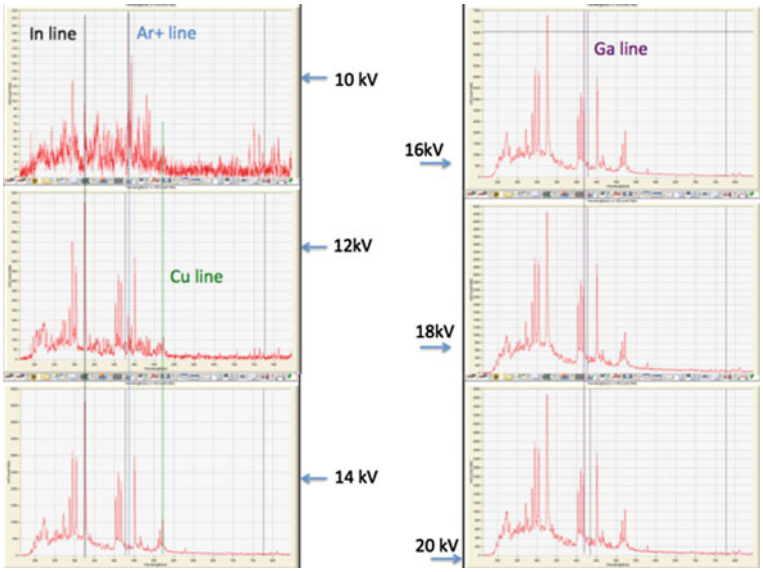

Fig. 17.5 Optical emission spectra of CIGS plasma at different acceleration voltages

stoichiometry transfer. The latter can be always obtained at low Ar flows (from 5 to 8 sccm) and in this range both Cu/In and Ga/In peak ratio are not affected by the gas flows.

17.4.3 PED Current

By measuring the PED e-beam current and voltage with the Rogowsky coil, the beam energetic distribution (*fast electrons* > ablation, *slow electrons* > evaporation) can be unambiguously identified.

This information is important to design and realize a new PED source, with a more efficient and highly energetic electron beam, optimized for the ablation of the CIGS target.

17.4.4 Faster Deposition

Aiming to increase the PED deposition/growth rate (currently limited to 15–20 Hz pulses frequency), the innovative idea was first to use a tubeless supersonic beam instead of a ceramic tube to guide the pulsed electron beam. The main problem is that a micrometric nozzle is required for the generation of the supersonic beam that rapidly tents to be blocked.

Commercial, custom made molybdenum aperture, selected for its chemical inertia, i.e. a disc of about 10 mm diameter, thickness around 0.1 mm and nozzle aperture of 20, 40 and 50 μm, have been tested in different working conditions. As expected, the use of the 20 μm nozzle gives the best results in terms of electron beam propagation and minimum gas load; however, the argon pressure in the supersonic beam source as high as 1000–2000 mbar is necessary, with a pressure increase in the vacuum chamber from 10^{-6} mbar to 10^{-4}–10^{-3} mbar. Clearly, the larger the nozzle, the more difficult the control of the beam.

During the ablation process at high voltage (>14 kV), in particular in presence of oxygen, the nozzle aperture only lasts a few minutes before obstructing, while using low power electron beams, no damaging of the Mo diaphragm has been observed, also in case of exposure to air.

Unfortunately, the threshold for the CIGS target ablation is 16 kV, (Fig. 17.6) and in these conditions the nozzle lifetime is limited to 30 min; after that, unavoidably the occlusion forms, due to massive erosion and material melting, irreversibly closing the aperture.

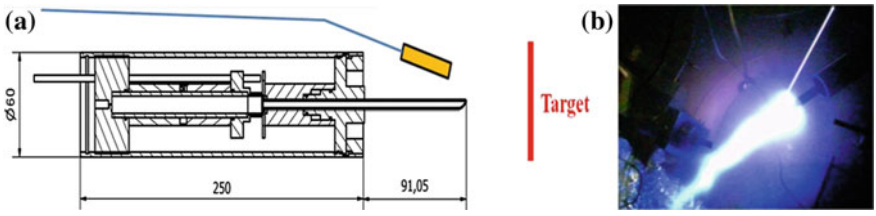

Fig. 17.6 **a** Scheme of the supersonic beam assisted PED and **b** test in vacuum

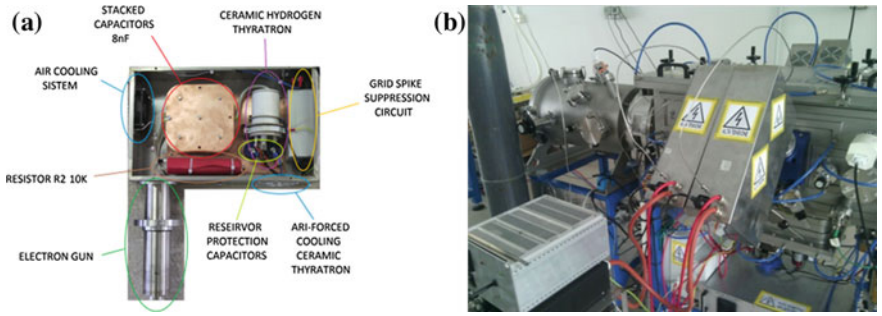

Fig. 17.7 **a** The new PED source and **b** the multi-PED system (4 new PED sources) installed at IMEM for large area CIGS-based TFSC fabrication

The same problem occurs by using a source made of quartz with a 50 μm nozzle. Again, its maximum lifetime is around 30–40 min, then the gas pressure sudden increases due to the formation of cracks around the nozzle.

Although the principle of the supersonic beam has been successfully demonstrated, this solution is considered not suitable for the production scale-up.

An alternative way to increasing PED deposition rate is to provide a more efficient control of the pulse generation to increase the pulsed frequency. The difficulty is mainly related to the necessity to manage a quick (transient of few ns) and fast (width of 100–200 ns) impulse of current at very high voltages (10–20 kV) and peak current (1000–2000 A). High voltage (HV) power supply can be only used up to 40 Hz, because of its high internal intrinsic resistance. A gas HV switch Thyratron is finally adopted, by far more complex to control, requiring different low/middle voltage supplies for proper working, but enabling a reliable and efficient control unit.

The radically new PED sources, fabricated in collaboration with Noivion s.r.l.,[1] show a good performance in the working conditions at frequencies up to 150 Hz (Fig. 17.7).

17.4.5 Deposition Chamber

The installation of the new PED sources could not fit the existing chamber, therefore a new deposition system has been designed and built. Aiming at the pre-industrial scale-up, it hosts 4 sources, able to deposit solar cells as large as 160×160 mm^2, on both rigid (glass) and flexible substrates (Fig. 17.8).

The preliminary results confirms that, by adjusting the PED sources geometry, it is possible to homogeneously deposit on 160×160 mm^2, corresponding to the size of a conventional Si-based solar cells.

[1] www.noivion.com

17.5 Developed Prototypes

The final upgrade provides a solution enabling a *dynamic* deposition from the *static* deposition of the multi-PED chamber in Fig. 17.8, by installing a flexible substrate holder composed of rotating wheels (motorised reel-to-reel apparatus, Fig. 17.9). The rotating speed is driven by the "in situ" film thickness measuring system, allowing the tape movement when the film reaches the desired thickness. The reel-to-reel motor is also connected to the PED source, switching on/off when the tape starts/stops.

The installation of the reel-to-reel substrate holder requires major changes in the vacuum chamber that has to be completely redesigned and built.

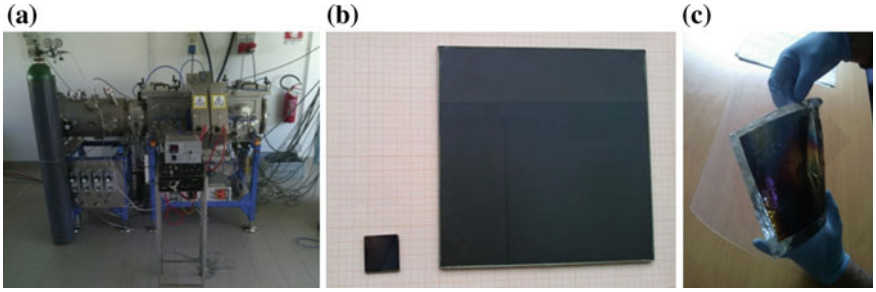

Fig. 17.8 **a** The new multi-PED system for large area (16×16 cm^2) CIGS-based TFSC. **b** The larger cells are deposited on aluminium foil and **c** transparent polymers (TEONEX)

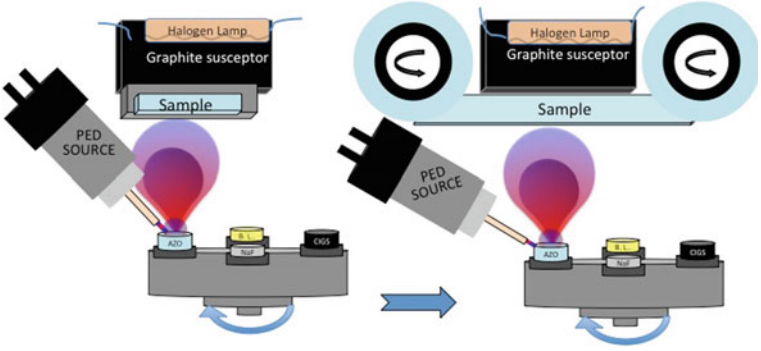

Fig. 17.9 Scheme of the evolution from static to dynamic CIGS deposition

17.5.1 Wheel Size Specifications

To design the radius of the wheels, an AFM combined with a mechanical buckling system (Fig. 17.10) is used to measure, in situ and in real time, the maximum bending curvature of CIGS-based TFSCs deposited on a 1 cm wide flexible stripe [23]. To determine the maximum curvature to which the device is irreversibly damaged, both topographical changes and electrical performances are tested during the deformation induced by the bending.

FEP bare stripes were first investigated to understand how the surface roughness changes with the angle subtended by the circular arc formed by the bended film (α). The roughness for $\alpha = 0°$ (flat stripe) is 10 nm, which increases linearly to 20 nm for $\alpha = 180°$ (maximum bending angle) due to the relatively large deformation of the polymeric stripe. In order to test different polymeric substrates in different conditions, PI (roughness 4 nm) was coated with 500 nm of Mo to test the back electrode behaviour versus bending, while ETFE was coated with ITO (indium tin oxide, 40 μm) and CIGS (4 μm) to test the behaviour of the CIGS solar cell. Mo film is invariant with respect to bending up to $\alpha = 70°$, then the surface roughness increases suddenly from 4 to 6 nm and the electrical performances irreversibly change. CIGS films are morphologically invariant versus bending up to $\alpha = 180°$, while the electrical resistance changes drastically after $\alpha = 70°$.

On the base of these experimental results, a critical angle α_C of 70° is set as limit to preserve both mechanical and electrical properties of Mo and CIGS films. This angle corresponds to a wheel radius of 1.5 cm, but a safer roll-to-roll system with 5 cm wheel radius has been realized to make it suitable for any polymeric substrates.

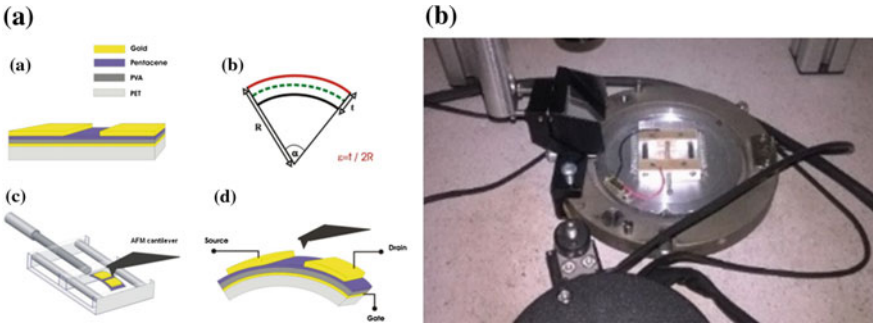

Fig. 17.10 **a** Scheme of the system to study the performance of flexible substrates versus bending and **b** mounted in the AFM basal plane

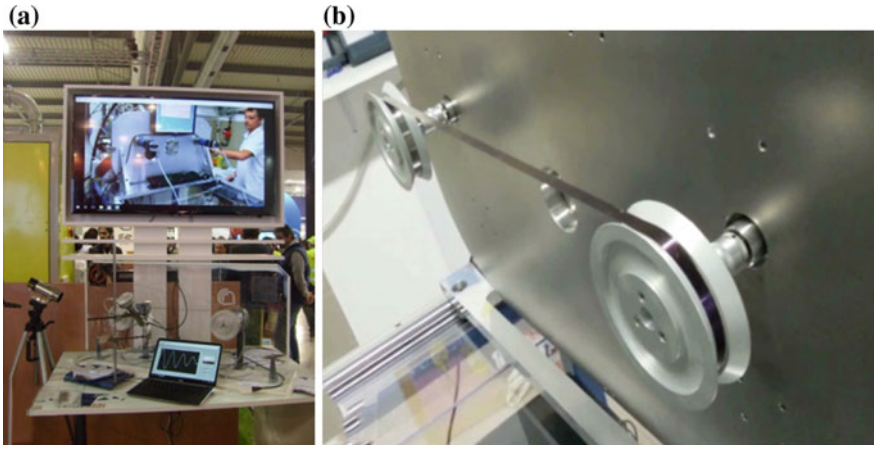

Fig. 17.11 Rolling CIGS prototype. **a** Simplified version presented at BIMU and **b** in operation

17.5.2 Automated Roll-to-Roll Movement

An enabling signal on the HV unit, switches on/off the pulsed electron ablation. The growth of thin films determines the movement of the flexible substrate, by interconnecting the PED source, the reel-to-reel motors and the thickness monitoring system. All the operations are controlled by a LabView program and a friendly user screenshot visualizes the cell final length and the time required to perform the whole process, allowing to change the parameters during the operation.

17.6 Testing of the Prototype System

Once defined the reel-to-reel wheel size and the hardware/software to control and synchronise the motor movement, the final prototype of the deposition system has been designed, realized and tested (Fig. 17.11).

The prototype is fully operating and the further optimization of the deposition of CIGS-based TFSC on various flexible substrates is currently in progress. The preliminary results, although still significantly lower than the 17% PV efficiency reported for small area, glass substrates, are promising. The main issue is represented by the bending of the substrate, since it induces some kind of defects. Indeed, despite the cells seem to be intact, the PV efficiency drops when the polymeric substrates bend. Further characterizations are in progress, both on the material and the device, such as DLTS (deep level transient spectroscopy) and EBIC (electron induced charge current). The first results also indicate that the adhesion of the interfaces (in particular Mo/CIGS) is critical, because the films frequently detach.

A simplified version of the prototype has been presented during the 30° BIMU Exhibition (Milano, October 6–8, 2016).

17.7 Conclusions and Future Research

The development of a new method to fabricate low cost, high efficient thin film solar cells is extremely ambitious, aiming to assign again an important role to the Italian companies in the strategic PV market, eventually using proprietary technologies. In this sense, the potential advantages of the PED compared to the currently available techniques can be summarized in a drastic simplification of the deposition process leading to a low-cost fabrication of CIGS-based TFSC. PED is particularly suited for the use of flexible substrates, thanks to the very low working temperature, allowing the deposition on a large range of thermo-labile polymeric substrates.

External and somehow unpredictable factors may determine the real impact of the presented results. In the PV market, often non-scientific factors strongly affects the diffusion of the solar plants, such as the rapid price changes of the PV cells/modules, the national economic policies (feed-in-tariffs) on the PV installations, the geo-political situations, the economic decision of the oil companies, etc. In any case, the direction clearly points to the use of the renewable energy.

Besides the thin film, flexible solar cells, it is worth recalling that there are other innovative devices with promising applications in the fields of BIPV and PIPV, such as the thin film semi-transparent bi-facial solar cells, where the PV conversion efficiency can be significantly increased by collecting light from both front and rear side of the solar cell. Again, by combining the low temperature PED and the use of unconventional transparent substrates, innovative PV products can be developed [24, 25].

Moreover, the space sector, where the Power/Weight ratio (Wp/gr) is the key factor may benefit from the development of solar cells on flexible, light substrates. It is important to stress, however, that in terms of efficiency, the CIGS-based flexible TFSC are not yet performing like the conventional rigid panels and the scientific community is strongly committed to improve the PV properties and the uniformity over large area.

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