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Monolithic interconnected modules (MIM) for high irradiance photovoltaic energy conversion: A comprehensive review

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ABSTRACT

Monolithic Interconnected Modules (MIM) are densely packed arrays of series interconnected photovoltaic (PV) cells that are manufactured on the same semiconductor substrate. This review presents the result of a prospective study whose objective is to provide an overview of the historical development and current state of the art of the MIM technology. The most outstanding works from the conception of the first MIM devices in the late 70s to the most recent ideas to date, including all relevant milestones achieved during these four decades, are reported. This review focuses on MIM devices that are designed for high-irradiance photovoltaic (HIPV) applications, such as concentrator PV (CPV), thermophotovoltaics (TPV), and laser power conversion (LPC), in which the highly dense series interconnection is particularly relevant in order to boost the output voltage without scarifying the receptor photoactive area.

1. Introduction

Monolithic Interconnected Modules (MIMs) have been extensively developed during the past few decades for high irradiance PV (HIPV) applications, which are characterized by a significantly high irradiance impinging on the PV converter. The most remarkable examples of HIPVs include concentrator PV (CPV) [1–3], thermophotovoltaics (TPV) [4,5], and laser-power-conversion (LPC) [6,7]. In these applications, the PV cell is illuminated by irradiances that typically exceed several tens of W/cm^2, i.e. 100's times the solar irradiance on Earth. Under these conditions, the PV cells produce extremely high current densities, and the fabrication of densely packed arrays of small PV cells becomes necessary in order to reduce (increase) the output current (voltage) of the module.

Several concepts have been developed to manufacture densely packed arrays comprising spare PV cells [8–13], most of them involving a relatively complex assembling technique. MIMs provide an effective alternative to these concepts, enabling a significant reduction of the module area devoted to cell interconnection; and notably simplifying the assembly of the full PV receptor.

In this article we review the historical development of MIMs, providing a compilation of references on this topic and summarizing the different technological options that have been developed during the last four decades. The purposes of this review are to overview and classify the different types of MIMs, to establish the current state of the art, and to identify the most promising future developments.

In Section 2, we summarize the main kinds of MIMs, introducing the main concepts related with this technology. Sections 3–6 describe the specific developments of MIMs based on Si, GaAs, InP, and GaSb substrates, respectively. Section 7 describes those activities on MIMs comprising III-V based multijunction subcells and finally, Section 8 provides a compilation of the most remarkable works along with a description of some possible developments envisaged for the future.

2. MIM technology overview

In an attempt to classify the different MIM technologies, in this article we pay attention to three of their main differentiating features: the semiconductor compound, the electrical isolation technique, and the final application.

Abbreviations: BPC, Back Point Contact; BSR, Back Surface Reflector; CID, Cell Isolation Diode; CLEFT, Cleavage of Lateral Epitaxy For Transfer; CPV, Concentrator Photovoltaic; DH, Double Heterostructure; ELO, Epitaxial Lift Off; EMVJ, Etched Multiple Vertical Junction; FF, Fill Factor; GFI, Grid Finger Interconnect; GPHS, General Purpose Heat Source; HCPV, High Concentrator Photovoltaic; HIPV, High Irradiance Photovoltaic; HCPVT, High Concentrated Photovoltaic Thermal; IMF, Interfacial Misfit; J_{SC}, Short-Circuit Current Density (A/cm2); LED, Light Emitting Diode; LCL, Lateral Conduction Layer; LPC, Laser Power Converter; MBE, Molecular Beam Epitaxy; MEMS, Microelectromechanical systems; MIM, Monolithic Interconnected Module; MJSC, Multijunction Solar Cell; MOVPE, Metal Organic Vapor Phase Epitaxy; PECVD, Plasma Enhanced Chemical Vapor Deposition; PV, Photovoltaic; QE, Quantum Efficiency; RIE-ICP, Reactive Ion Etching in Inductively Coupled Plasma; RTG, Radioisotope Thermoelectric Generator; RTPV, Radioisotope Thermophotovoltaic; SI, Semi Insulating; SOE, Secondary Optical Element; SOI, Semiconductor On Insulator; TPV, Thermophotovoltaic; V_{OC}, Open-Circuit Voltage (V); WSI, Wafer Scale Integrated

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Attending to the application, we found three main types of MIMs: those used in CPV, TPV or LPC environments. Regarding CPV, MIMs have been developed for dish/tower CPV power generation systems, where the sunlight is concentrated by a factor as high as several hundreds on highly efficient, actively cooled PV arrays of relevant size of a few tens of cm^2. Dish/tower-CPV systems are an alternative to conventional CPV, with the difference of a single concentrated light spot per systems instead of multiple concentrated spots, each of them illuminating individual cells. The large PV receptor area of dish/tower CPVs makes MIMs perfectly suited for this application, to minimize the area of the receptor dedicated to the interconnection between cells. In TPV applications, the diffuse radiant heat originating from an incandescent source is converted into electricity by infrared-sensitive PV cells. In this case, the irradiance strongly depends on the source temperature and emissivity, ranging from ~10 W/cm^2 for 1000 °C to ~100 W/cm^2 at 2000 °C. Due to the nature of the irradiation, TPV applications are typically extended to large areas, where the use of MIMs enables higher collection efficiency and output voltage. Finally, LPCs makes wireless power transfer from the generator to remote loads possible (e.g. satellites, dangerous environments, etc.) by using a laser power source. LPCs convert laser power into electricity at very high efficiencies (> 50%) and may operate in the broad range from ~1 to ~200 W/cm^2, depending on the laser power output. In this case, MIMs enable to boost the output voltage avoiding the use of DC/DC converters. Another possible field of application for HIPV MIMs is microelectromechanical systems (MEMS), which require a high voltage DC power supply. In this case, MIMs enable the miniaturization of high voltage, chip-integrated power supplies.

Attending to the semiconductor compound, we find two main categories: the ones based on Si and the ones based on III-V semiconductor substrates. Si substrates were mostly used during the early times of MIM development technology and they were typically devoted to solar applications. However, the advent of III-V semiconductors in the early 80's rapidly impacted the MIM development and most subsequent works focused on III-V-based devices in order to take advantage of their greater versatility regarding ternary and quaternary alloying and the availability of different substrates. Among the III-V options, only three substrates have been used so far to fabricate MIMs: GaAs, InP, and GaSb. A number of compounds have been grown by molecular beam epitaxy (MBE), metal organic vapor phase epitaxy (MOVPE), and liquid phase epitaxy (LPE), to produce different types of III-V-based MIMs. For instance, GaAs substrates have been used to fabricate (In)GaAs and GaInP devices, suitable for most visible and near-infrared applications, e.g. most CPV and some LPCs. In applications requiring spectral response at longer wavelengths, InP and GaSb have been used to grow different kinds of compounds with bandgaps ranging from 0.5 to 0.75 eV, such as InGaAsSb on GaSb (used in TPV applications) and InGaAs on InP (widely used in TPV and LPC applications).

Attending to the electrical isolation of MIMs, we find three main categories: those based on semi-insulating (SI) substrates, those using cell-isolation diodes (CID), and those based on semiconductor-on-insulator (SOI) substrates. The most robust and simple solution is the use of SI substrates, which are manufactured by incorporating certain defects in the semiconductor lattice that cause the Fermi level to be pinned close to the center of the bandgap, emulating the case of a perfectly intrinsic (highly resistive) semiconductor. In this case, the electrical insulation between subcells is readily accomplished by means of wells etched down to the substrate. These wells are covered by an insulating layer to protect the exposed perimeter area of the subcells, allowing the deposition of metals to series-connect adjacent subcells without short-circuiting (Fig. 1). The use of SI substrates is the most common choice for manufacturing MIMs on GaAs and InP substrates, for which commercial SI substrates are readily available. Unfortunately, no high quality SI substrate exists on Si or GaSb. Thus, they require other strategies such as the integration of CIDs to create a reverse polarity of the substrate with respect to the subcell base that electrically isolate adjacent subcells. One crucial limitation of this design concerns the CID reverse-bias operation: if the CID is illuminated, there will be a current path through the CID that could short-circuit the corresponding subcell. Besides, there is a limit in the number of subcells that can be series-connected corresponding to the CID breakdown voltage. Other works used SOI substrates, which are manufactured by bonding the active semiconductor layers to an insulating holding substrate, such as glass or ceramics. In this case, the electrical isolation is performed similarly to the case of SI substrates. This strategy typically involves some kind of epitaxial lift off (ELO) process to transfer the very thin active epitaxial layers to the final substrate.

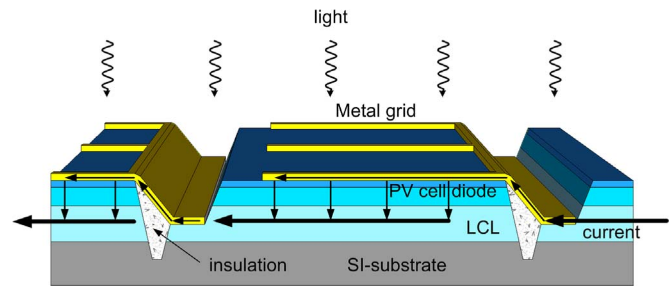

Fig. 1. Operation principle of a typical MIM based on SI-substrate.

3. Si-based MIMs

One of the first methods to fabricate Si MIM devices was patented by Riel in 1970 [14] and utilized the CID strategy (Fig. 2-a). In order to mitigate the possible short-circuits caused by illuminated CID, their minority carrier lifetime had to be reduced below 10 ns and they had to use very thick layers, at least twice the diffusion length, as proposed by Chiang et al. in 1979 [15].

In a series of publications dated from 1976 to 1983 [16–21], Warner proposed two alternatives to the designs by Riel and Chiang based on the use of SOI substrates. One of the Warner's designs (Fig. 2-b) used doping wells for the lateral isolation of the subcells. For producing these wells by conventional diffusion doping processes it was necessary to polish the Si wafer until reaching a thickness of ~30 µm. Although still based on CID isolation, in this design, the use of CID was restricted to the adjacent subcells, thus mitigating illuminated CID issues because, under this configuration, they are shadowed by the metallic grid. In 1979, Wada et al. [22] proposed an alternative to Warner's designs in which lateral isolation was carried out by doping from the two sides of the wafer simultaneously. This enabled very deep isolation wells and consequently avoided the requirement of very thin wafers on SOI substrates, at the expenses of requiring a more complex photolithographic process. Later on, Warner proposed a simpler approach for selective deep diffusion using an Al thermomigration technique [18]. In spite of the improvements with respect to the original design by Warner, all the above described designs still require reverse junction electrical isolation, with the associated shunting risks.

A second design proposed by Warner consisted on creating isolation baskets or wide grooves, the so-called etched multiple vertical junction (EMVJ), in which the active device was confined (Fig. 2-c). A similar approach was proposed by Kaplow and Frank, in a journal article [23] and in a series of patents dated from 1978 to 1979 [24–27]. This kind of devices were fabricated and tested under concentrated sunlight (300 suns) to reach conversion efficiencies above 19% [23]. A similar concept was proposed by Chappell [28] (Fig. 2-d) except for using substantially different processing steps that involved ionic implantation and anisotropic chemical etching. At the end, solar MIMs were fabricated using this concept, demonstrating efficiencies of 12.2% under illuminations of 300 suns [28]. In both designs,