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At present renewable energy sources consist mainly of hydro power and wind energy, with the latter becoming increasingly important. However, the number of solar cells being produced yearly (in terms of watts produced by these solar cells under a standardized spectrum) has been growing consistently over the last 10 years, with growth rates between 25 and 70%/year; for 2005 solar cell production reached 1.7GW. This terrestrial photovoltaic (PV) market is currently dominated by flat plate modules incorporating Si solar cells. However, to sustain the present growth rate of terrestrial PV, the use of expensive semiconductor material must be minimized, necessitating the development of new technologies.

Towards Highly Efficient 4-Terminal Mechanical Photovoltaic Stacks

According to all energy scenarios for the coming decades, made up by leading instances (*e.g.* White Paper European Commission), energy agencies (*e.g.* International Energy Agency) and R&D institutions the part of renewable energy sources within future energy generation schemes is expected to grow. Such growth is a necessary condition to counter problems related to the exhaustion of fossil energy sources (mainly oil) and to CO_2 emissions, and to tackle the difficulties associated with a further build-up of nuclear capacity.

Nowadays the part of renewable energy sources within the energy supply consists mainly of hydropower and wind energy, the latter becoming increasingly important. However, the number of solar cells being produced yearly (in terms of Watts produced by these solar cells under a standardized spectrum) is growing consistently the last 10 years with growth rates between 25 up to 70%/year, and for 2005 the yearly production of solar cells has reached 1.7GW. This terrestrial photovoltaic (PV) market is currently dominated by flat plate modules incorporating Si solar cells. However, in order to sustain the present growth rate of terrestrial photovoltaics, the use of expensive semiconductor material must be minimized, necessitating the development of new technologies.

Multijunction Photovoltaic Stacks for Terrestrial Applications

A very promising approach to increase the conversion efficiency is the use of high-efficiency multi-junction photovoltaic stacks. The basic idea of multi-junction photovoltaic devices is to use a stack of different materials (with different bandgaps) such that every solar cell in the stack absorbs part of the incident spectrum. By choosing a suitable combination of bandgaps for the different materials, this results in an improvement of the conversion efficiency over the single-junction approach.

The present state-of-the-art consists of a triple-junction cell, made by depositing InGaP and GaAs cells lattice-matched on a Ge substrate. A Ge cell is realized during deposition. The resulting triple-junction InGaP/GaAs/Ge cells have average production conversion efficiencies of approximately 30% (AM1.5). These cells are currently mainly being used for power generation in space applications, where their high efficiency and low weight make them the preferred solution. Such multi-junction cells are far more expensive than Si solar cells. However, they can become cost-competitive with Si flat plate modules for terrestrial applications if the incident light is concentrated on the high-efficiency cell (using refractive or reflective optical systems), given that the concentration factor and solar cell efficiency are sufficiently large. This is illustrated in Figure 1.[1] The higher cost of the multijunction cells is in this case compensated by their higher efficiency resulting in a reduction of the number of expensive concentrating systems needed to obtain a certain power level.

In order to further improve on the conversion efficiency of present multijunction photovoltaic stacks, a number of R&D groups worldwide aim at including a fourth junction in between the GaAs and Ge cell. This approach is however hindered by the lack of a lattice-matched 1.0eV material with suitable material quality. To handle this problem, even 5- or 6-junction cells are envisaged. Although this can certainly work from a principal point of view, the growth control requirements to obtain current matching are extremely severe.

4-Terminal Mechanical Stack

Alternatively, a 4-terminal mechanical stack consisting of separately contacted top and bottom cells is an attractive solution. The stack structure could be like the one shown in Figure 2. It is compatible with high efficiencies and allows extracting the power from separately connected bottom and top cell modules. This allows for the extraction of the full current generated by a separately connected Ge bottom cell, which is not the case in a monolithically stacked triple-junction cell. In the latter approach the extracted current is limited to the value generated by the current-limiting junction. This is due to the current-matching requirement imposed by the series connection of the different cells. In a state-of-the-art triple-junction cell, the current-limiting junction is either the InGaP or GaAs cell (depending on the thickness of the InGaP cell and the exact incident spectrum); while the Ge junction has the potential of generating a current roughly double as high.

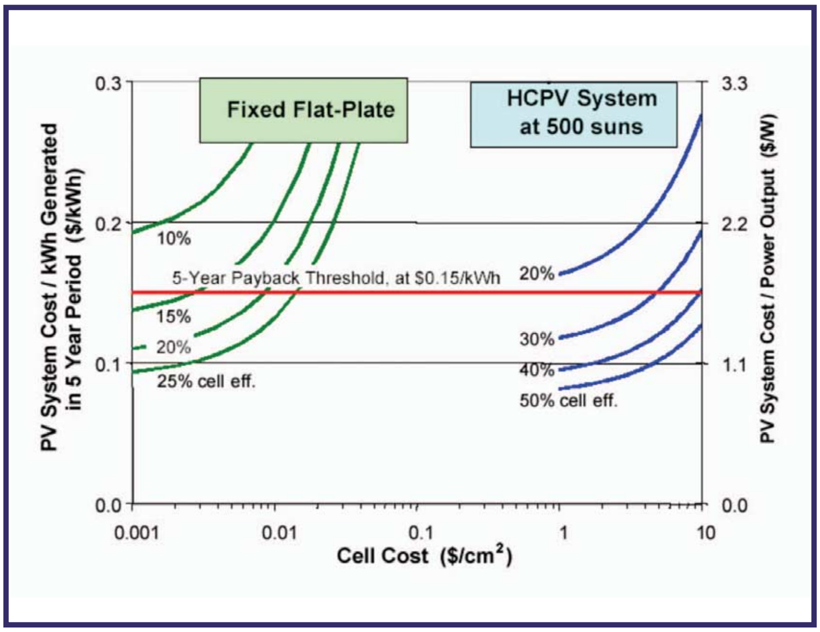

Figure 1. Cost comparison between Si flat plate and III-V high concentration PV systems.[1]

Both top and bottom cells for use in a mechanical stack as shown in Figure 2 are currently being developed at IMEC.

Thin Dual-Junction InGaP/GaAs Top Cell

The dual-junction top cell is an InGaP/GaAs solar cell, optimized for operation under high

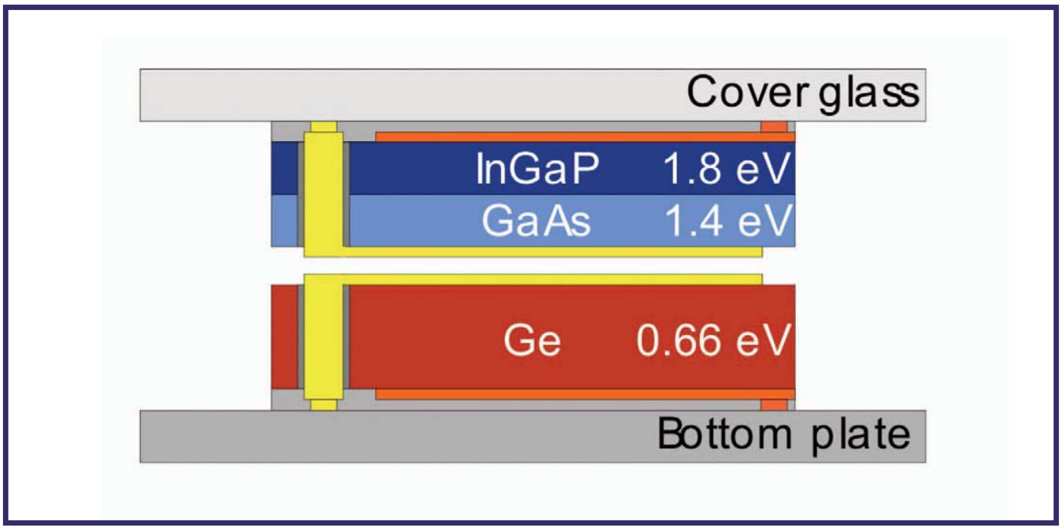

Figure 2. Schematic cross-section of the basic photovoltaic stack under development at IMEC.

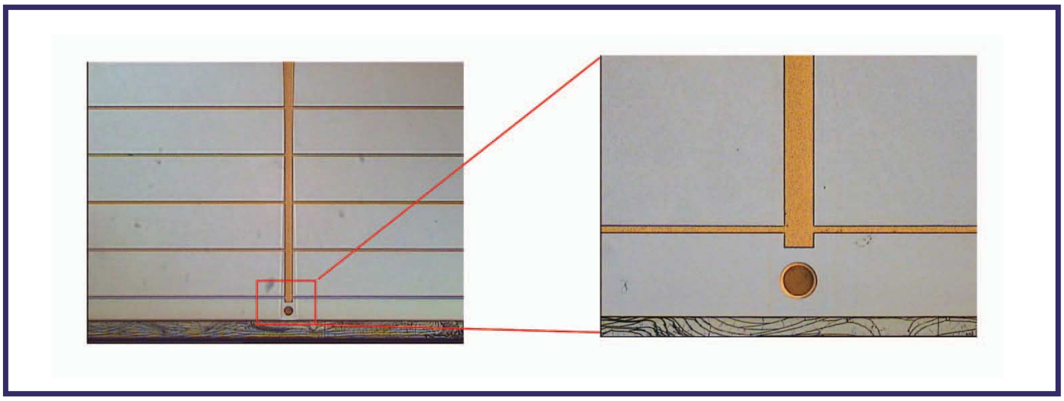

Figure 3. Thinned-down, one-side contacted GaAs solar cell. The top contact finger grid can be seen, as well as the wrapped-through back contact.

concentration. The cell is realized by epitaxial deposition of the solar cell stack on a Ge substrate using MOVPE growth and subsequent processing. An important concept in IMEC's approach to achieve a high-efficiency mechanically stacked cell is the removal of the Ge substrate on which the InGaP/GaAs top cell will be realized, resulting in a minimization of the infrared absorption in the top cell.

This is necessary to ensure an optimal transmission of this infrared radiation to the bottom cell. After epitaxial growth of the InGaP/GaAs cell stack and subsequent top contact processing, a carrier is (temporary) bonded to the top of the cell, and the Ge substrate can be fully removed using (wet or dry) selective etching. This way, we end up with a very thin (3–5 Ω m) dual-junction InGaP/GaAs top cell. Care is taken to ensure that front and back contact grids are optimally aligned with respect to each other, to minimize the shadowing losses towards the bottom cell.

As a first demonstration of IMEC's processing technology, a one-side contacted single-junction GaAs cell with a total thickness of ±4 Ω m has been developed (**Figure 3**). Because the cell is so thin, it is relatively straightforward to bring the back contact to the top of the cell using a wrap-through via opening. This one-side contacted cell layout facilitates both the stacking of top and bottom cell, as no interconnects need to be put in between top and bottom cell, as well as the module interconnection.

Highly Efficient Single-Junction Ge Bottom Cell

The bottom cell consists of a separately connected Ge bottom cell (**Figure 4**). The developing activities at IMEC resulted in the realization of stand-alone single-junction Ge bottom cells with a world-class conversion efficiency of 8–8.5% (and an excellent open-circuit voltage of 260–270mV) under the AM1.5 spectrum. This result was obtained by the incorporation of innovative surface passivation and contacting technologies,[2] which are key in attaining the optimal performance for a Ge solar cell. An n-p solar cell structure is realized in a p-Ge substrate by P diffusion from a spin-on dopant source.

Front surface passivation is obtained by depositing a layer of amorphous Si, through which the Pd/Ag contact grid is subsequently fired. Al is deposited as a backside contact, and upon annealing automatically also generates a back surface field that efficiently passivates the backside of the cell. Development of a one-side contacting technology scheme for these Ge solar cells, realized in thin (100 Ω m) substrates is planned in the near future.

Stacking the Cells on Top of Each Other

Next to the development of the dual-junction InGaP/GaAs top cell and single-junction Ge bottom cell, the stacking of these cells on top of each other is an important requirement to obtain optimal performance for the mechanically stacked cell. Optical coupling of the infrared light into the bottom cell is key in attaining a high current from this bottom cell. DC93-500 silicone sealant glue with a transmission of >96% in the 400–1800 nm range is used to attach both cells on top of each other, while the use of optimized anti-reflective coatings at the different cell surfaces limits the reflective losses in the relevant wavelength range.

Both top and bottom cell can be processed right up to the final step on full 4-in substrates; for the

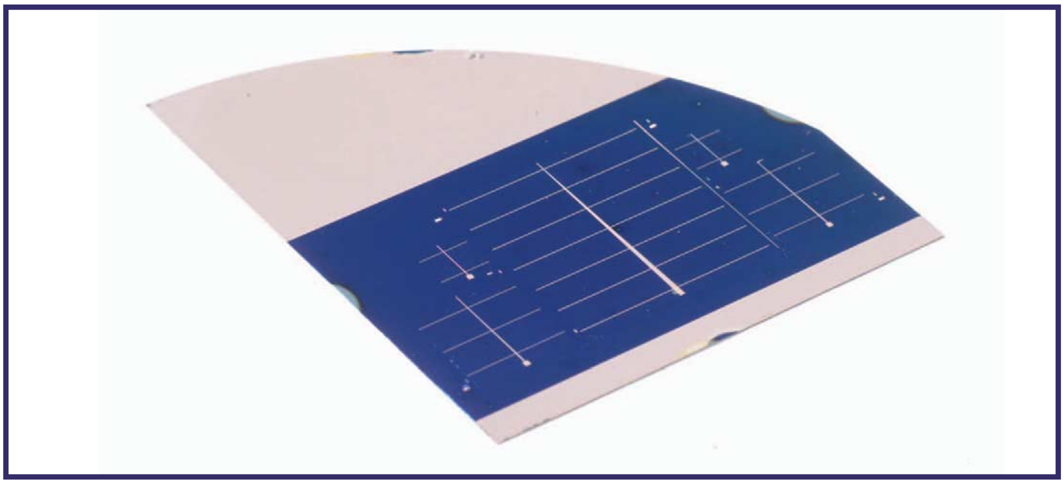

Figure 4. Photograph of the stand-alone Ge bottom cell.

top cell this implies a temporary bonding to a carrier substrate to ensure sufficient mechanical strength after thinning of this cell. Both 4-in substrates are to be bonded together after completion of cell processing, after which dicing to individual mechanically stacked solar cells is performed. Finally, interconnects can be applied to both one-side contacted cells, and a cover glass (or secondary optics element) can be put on top of the stack.

Improved Solar Stack Efficiencies and Other Benefits

According to our calculations, an optimized mechanical stack layout will allow for a single-junction Ge bottom cell efficiency of 4–5%, compared to the typical 2–3% efficiency of the Ge bottom cell in state-of-the-art monolithic triple-junction cells. This, together with a reproduction of present state-of-the-art dual-junction InGaP/GaAs solar cell efficiencies, allows a 2–3% efficiency gain over present monolithic triple-junction cells. Top and bottom cells can be separated in two different circuits, or can be combined in series and parallel to match voltage and current.

A final advantage of the mechanical stack concept that should be mentioned is an inherent modularity which can be used to advantage: the currently used single-junction bottom cell can in a later stage be replaced by a more efficient dual-junction (*e.g.* Ge/Ge or InGaNAs/Ge) cell in a straightforward manner, without necessitating far-reaching modifications to the InGaP/GaAs top cell. This means that our solar cell concept is compatible with final AM1.5 efficiencies of >35%.

Conclusion

The development of innovative low-cost PV technologies is crucial to supply the growing need of terrestrial photovoltaics. III-V high-concentration multijunction PV stacks can be a cost-effective solution provided that both concentration factor and solar cell efficiency are sufficiently large.

Improved conversion efficiencies can be obtained by separately contacting top and bottom cells, resulting in a so-called 4-terminal mechanical stack. IMEC is developing the technologies to realize both top (InGaP/GaAs) and bottom (Ge) cells and to stack the cells on top of each other.

A key component is the stand-alone Ge bottom cell realized with world-class conversion efficiency of over 8%. The solar cell concept will allow final AM1.5 efficiencies as high as 35% or more.

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