Lattice-matched SiGe on GaAs for triple-junction CPV solar cells

Dr Andrew Johnson and Mr Robert Harper explain how IQE has demonstrated the first triple-junction photovoltaic device with an epitaxial bottom cell grown lattice matched on a 6” GaAs substrate.

We describe a novel patented approach to the epitaxial growth of multi-junction III-V photovoltaic structures, namely the use of epitaxial silicon-germanium (SiGe) grown lattice matched to large-area GaAs substrates for the bottom cell of such devices.

There are several advantages to this approach over the conventional use of an active germanium substrate. These include precise control over SiGe doping, with consequent benefits in overall device performance, and also the ability to lift off the epitaxial layers from the substrate and allow GaAs substrate re-use.

Multi-junction solar cells

Multi-junction solar cell technology based on III-V semiconductors has made significant strides in the last 20 years, and the world record conversion efficiency for a solar cell of 41.6% has recently been demonstrated by Boeing subsidiary Spectrolab Inc using this type of device (independently verified by NREL). These devices are typically triple-junction structures grown on germanium substrates.

Whilst predominantly being used for space applications at the present time, this technology is poised for massive expansion in the field of terrestrial power generation, in the form of concentrated photovoltaics (CPV). CPV uses mirrors or lenses to concentrate the sun’s radiation, giving the dual advantage of reducing the III-V cell area requirement while increasing the conversion efficiency of the cell. This offers the possibility, under certain operating conditions, of significantly reducing the cost per Watt of energy produced when compared with other forms of renewable energy generation.

The formation of multi-junction cells is typically achieved by using an active germanium substrate which is used to form the bottom cell of such a device by diffusion of the Group V material from the overlying III-V semiconductor layers to form the n-type emitter of the p-n junction. This process is, by its very nature, difficult to control and is the subject of several patents. The other cells would then be formed using a conventional epitaxial approach, usually with a GaAs middle cell beneath an indium gallium phosphide (InGaP) top cell. Each sub-cell is connected via a low-resistance tunnel contact, and the rest of the structure consists of various windows, contacts and back surface fields, arranged to optimize the solar photovoltaic device performance.

The conventional diffusion-doped Ge approach also provides a bottom cell that over-produces photocurrent compared with the other sub-cells. Whilst this means that the overall triple-junction device can be optimized by current matching the top two cells, it also suggests that overall device efficiency is being lost in a device where absolute efficiency is all important.

There are several approaches being investigated where multi-junction device architecture is being adjusted to better match the device to the solar spectrum. Examples are the use of metamorphic structures on both GaAs and Ge substrates and also the inverted metamorphic (IMM) approach where the device is grown inverted and removed from the GaAs substrate. All of these technologies rely on lattice-mismatched growth, which adds cost, complexity and the distinct possibility of reduced yields in volume manufacturing. In an industry where cost per Watt generated is one of the key drivers, these technologies might never be able to achieve the desired cost points.

IQE has approached these problems from a different direction. As IQE has extensive experience of growing Si, Ge and SiGe epitaxially at our IQE Silicon facility in the UK, we have used this expertise to develop the means of growing the bottom cell of a triple-junction...
CPV device, lattice matched to a GaAs substrate. A schematic structure for such a triple-junction device is shown in Figure 1. Lattice-matched SiGe (~2% Si) a few µm thick is grown onto Zn-doped GaAs substrates (as described below), forming the bottom cell of a triple-junction device.

Virtual substrates

The SiGe layers are epitaxially grown using low-pressure chemical vapor deposition (LPCVD) in an ASM Epistem reactor and can be doped in-situ using diborane and phosphine to produce p- and n-type layers accordingly. Composition, thickness and cross-wafer uniformity of the SiGe is checked using high-resolution x-ray diffraction. The wafer is then transferred to an Aixtron 2600 Planetary III-V MOCVD reactor using a proprietary technology to protect the SiGe surface. As a proof of concept, these SiGe virtual substrates have then been treated exactly like a conventional Ge solar PV substrate, using diffusion of the overlying group V material to create the p-n junction in the SiGe epilayer. It is then possible to grow the top two cells of the triple-junction device in the MOCVD reactor using a standard growth recipe. The only modifications required are to change the compositions of the III-V materials so that they are lattice matched to the GaAs substrate rather than for Ge. For example, the middle cell would be made entirely of GaAs rather than InGaAs, which would normally be used on Ge. If lattice matching of the SiGe layer is carried out properly then there is usually no problem growing the III-V material, with the morphology of the final layer looking identical to similar epilayer structures grown directly on Ge.

Having successfully grown high-quality CPV epilayer structures onto SiGe on GaAs, these wafers were processed using a standard CPV fabrication line by one of our major partners. The only difference between this approach and a conventional CPV cell on Ge would be the back contact metallization, which is required to achieve an acceptable ohmic contact to the p-GaAs substrate.

Devices have been fabricated into cells measuring about 5mm x 5mm and 10mm x 10mm and subjected to flash I-V test up to 300 suns concentration. Figure 2 shows the I-V characteristic for a 10mm x 10mm device operated at about 200 suns. The results match those achieved using a similar epitaxial structure grown on Ge in the conventional manner, which exhibit absolute conversion efficiencies of about 38%.

Interestingly, the devices grown on GaAs exhibit a slightly higher VOC than a similar device grown on a Ge substrate, presumably due to the slight changes in energy bandgap that occur when adjusting the material compositions to obtain lattice matching. In addition, the GaAs-based devices tend to exhibit higher fill factors than the corresponding devices on Ge, with values of about 90% being typical at ~200 suns concentration, compared with 87–88% for a 'conventional' device.

This is the first demonstration of a triple-junction (3J) photovoltaic device with an epitaxial bottom cell, grown lattice matched to a GaAs substrate. Further improvements in the overall device performance are imminent — the same modifications that can be used to achieve improved efficiency in a conventional 3J cell are directly attributable to this device structure, and these improvements are in progress.

While this device still uses a diffused SiGe junction for the bottom cell, the epitaxial nature of this bottom cell now offers the opportunity of greater control of the doping of that cell and hence performance enhancement. IQE has a proprietary process that can be used to reduce or largely eliminate the Group V diffusion when growing III-V materials directly onto Ge or SiGe. This can be used to enable the growth of the bottom junction in an all-epitaxial fashion, giving significantly greater control of the doping and thickness profiles for the junction and thus enhanced device performance.
Additional opportunities

There are other opportunities that can then be achieved over conventional triple-junction devices using a passive Ge substrate. The ability to grow the bottom cell epitaxially also enables the growth of other layers that can assist the overall device performance. Such enhancement layers are wide-bandgap windows, tunnel contacts and back-surface fields, all of which can be grown epitaxially beneath the bottom SiGe cell p-n junction. This approach is not achievable with conventional triple-junction photovoltaic devices. All of these technologies are currently under investigation at IQE.

One of the major challenges facing the embryonic CPV industry is how to quickly reduce the cost of installing systems and to achieve the desired cost/Watt to enable CPV to compete directly with other energy generation technologies.

The whole point of using optical concentration in CPV is to reduce the requirement for III-V semiconductor material, but the overall cost proportion of the cell in a CPV system is still significant. Similarly, the cost breakdown of the III-V photovoltaic cell shows that the substrate cost for a CPV epiwafer is a very significant proportion of the overall cell cost.

To this end, this SiGe/GaAs technology is ideally suited to substrate removal and re-use. The epitaxial growth of dissimilar materials offers the prospect of reliable substrate removal through a range of techniques. IQE is investigating this approach using the SiGe technology with layers that can be selectively etched to enable reliable substrate lift-off, and we are investigating this technology with various partners.

Another benefit of the growth of high-quality epi on GaAs substrates is the fact that low-cost, 6” wafers are readily available in large volume from a number of vendors. As already stated, one of the key challenges for CPV is to achieve an acceptable cost-point, to enable energy generation at a cost that the market will be willing to pay. In common with most other semiconductor technologies, one of the main ways to achieve this is through the use of ever larger-diameter substrates, yielding larger device numbers per run. In contrast to GaAs, 6” Ge wafers are not yet readily available in large volume and at low cost, although this will occur as the CPV market expands. IQE has already demonstrated successful epitaxy of triple-junction photovoltaic devices onto 6” GaAs substrates, using its SiGe epitaxial technology. Performance of these devices matches similar structures grown onto 6” Ge substrates in consecutive MOCVD runs, and is close to the performance demonstrated on 4” Ge and GaAs substrates. This is the first demonstration of a lattice-matched, triple-junction device grown on 6” GaAs.

Figure 2: I-V curve for a 10mm x 10mm cell operated at x200 suns.

Figure 3: P-V curve for 10mm x 10mm cell operated at x200 suns.

Figure 4: Epitaxial SiGe CPV cells manufactured on 4” GaAs substrates.
Future work will concentrate on improving the bottom cell performance of the SiGe/GaAs structure, using some of the techniques described above. The advantage of this technology is that any improvements demonstrated in conventional diffused-junction photovoltaic devices grown on Ge substrates can quickly and easily be incorporated into the SiGe/GaAs structure without too much development. Similarly, any customers that have their own intellectual property or layer structures related to multi-junction devices can easily and quickly incorporate their technology onto this SiGe/GaAs platform to gain the benefits of enhanced device performance and the ability to lift off the epitaxy from the substrate. In addition, IQE will continue to investigate the use of this technology for reliable and cost-effective layer transfer with subsequent substrate re-use.

**Summary**

IQE has demonstrated a novel approach to the epitaxial growth of multi-junction photovoltaic devices, namely the use of an epitaxial SiGe bottom cell grown onto a GaAs substrate. Device performance is already very close to the best that is currently available on the market using conventional devices on Ge substrates. This technology can easily be grown in large volume and has already been demonstrated on 6” GaAs substrates.

The ability to engineer the bottom cell using conventional epitaxial processes also offers a clear opportunity to increase the overall device performance, and further device enhancements can easily be transferred into the top two sub-cells of the device.

**Figure 5: Authors Dr Andrew Johnson and Mr Robert Harper.**

This is an exciting development that offers significant scope for further device improvement and also reduced cost of manufacture.

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Authors: Dr Andrew Johnson, CPV Technology Director, and Mr Robert Harper, Project Manager (Solar Products), IQE.

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