GaAs Solar Cells with High Carrier Collection Grown on Unpolished, Spalled Ge Substrates

Preprint

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GaAs Solar Cells with High Carrier Collection Grown on Unpolished, Spalled Ge Substrates

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***Abstract* — Decreasing the cost of single-crystal substrates has long been sought for III-V solar cells. Controlled spalling is a possible pathway for epitaxial liftoff, which would help reduce costs, but chemo-mechanical polishing after liftoff tends to limit the impact. Growth on an unpolished spalled surface would be an additional step toward lower costs, but it is crucial to show high efficiency solar cell devices on these unprocessed substrates. In this study, we spalled 2 inch Ge wafers using a Ni stressor layer, and GaAs solar cells are grown by HVPE on the spalled Ge surface without any other surface treatment. We show a 12.8% efficient device, without anti-reflection coating, with equivalent quantum efficiency as identical devices grown by HVPE on non-spalled GaAs substrates. Demonstrating a high carrier collection on unpolished spalled wafers is the first step toward reducing substrate-related liftoff and polishing costs.**

I. Introduction

III-V solar cells have demonstrated the highest efficiency of any photovoltaic device to date, but high cost has restrained their applications to niche markets consisting mainly of high concentration and space power systems[1]. A major portion of the price is the deposition cost, which can potentially be lowered using hydride vapor phase epitaxy (HVPE),[2] a high-throughput, low-cost epitaxy technique that has demonstrated single-junction GaAs solar cell efficiencies > 24% [2]–[4]. However, the cost of the single-crystal substrate used for device growth remains very high. One possible path to reduce substrate-related costs is to combine epitaxial liftoff using controlled spalling with growth on unpolished surfaces that reduce the cost of substrate reuse [5]. Spalling uses a stressor layer deposited on a substrate, so that when a crack is initiated it propagates parallel to the surface. This process takes less than a second to occur, can be integrated in a straightforward manner in fabrication lines, and it has been shown in Ge (100) wafers[6]. The spalling approach, compared to the traditional chemical epitaxial lift-off, potentially has higher throughput and scalability, and thus can be a feasible process in large scale manufacturing of photovoltaic devices. The spalling process, however, does not leave behind an equivalent surface to an epi-ready wafer. Invoking a chemo-mechanical polishing (CMP) processing step at this stage is likely cost-prohibitive for the use of III-V devices in much larger markets than where they exist today[1]. Therefore, growth on a spalled surface, without additional processing, could reduce the number of costly steps associated with wafer reuse. CMP may account in fact for a cost of 8-16$ per reuse.

While solar cells grown on reused spalled Ge have been demonstrated previously, only a relatively low efficiency has been shown, and it did not probe the limiting factors of cells on a spalled substrate, due to issues of growth on Ge[7]. In this paper, we present the growth of a GaAs solar cell on spalled Ge, as well as the performance of the photovoltaic devices to assess the issues limiting the efficiency.

II. Experimental Methods

The surface of a 2-inch diameter (100)-oriented Ge substrate (p-type doping, 6° offcut) was cleaned for one minute using a 2:1:10 volumetric solution of NH_4OH:H_2O_2:H_2O. A nickel stressor layer was electroplated on the polished surface of the wafer using a circular jig with front contacts and plating diameter of 1.71 inches[8]. The plating time and current density were t = 2.75 minutes and J = 80 mA/cm^2, respectively. The sample underwent a 3-min post-plating etch step in a freshly made 2:1:10 solution [7]. We completed the controlled spall using a roller and a Kapton tape adhesive for the handle[9]. The sample was then loaded directly in the growth reactor for III-V epitaxy without further surface processing.

Fig.1 shows the device structure. Growth was conducted at 650°C in a custom-designed dual chamber HVPE reactor[10], [11]. While the lattice constant of GaAs is close to Ge, it differs by ~ 0.1%: a 1μm-thick GaAs buffer layer was thus grown first on the spalled Ge. The buffer was followed by an inverted GaAs solar cell, grown at a rate of ~ 1.1 μm/min, between InGaP cladding layers.

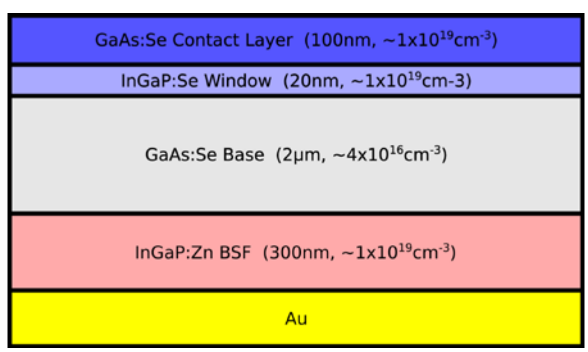

Figure 1. Device schematic of the heterojunction GaAs solar cells.

The film was characterized by X-ray diffraction (XRD) to determine the degree of mismatch of the epitaxial films. After removing the epi-layers from the substrate, devices were processed following a procedure analogous to the one described previously in Ref.[12]. The cell size is 0.25cm^2. The quantum efficiency (QE) and specular reflectance measurements were obtained via a custom-built QE setup, while the current density-voltage (*J-V*) performance was measured on an XT10 solar simulator, calibrated to simulate the AM1.5G spectrum at 1000 W/m^2.

III. Results and Discussion

Fig. 2a shows the external and internal QE, as well as the reflectance for a single-junction GaAs solar cell grown on unpolished, spalled Ge. The IQE of a representative GaAs cell grown on GaAs by HVPE is included as well for comparison. The IQE of the device grown on the unpolished surface is similar to the best GaAs cells grown by HVPE on GaAs[2]. The high IQE indicates that minority carrier lifetimes are long enough to achieve full collection of the absorbed carriers. Since we deposited no anti-reflection coating (ARC) on the sample at this time, the reflection is ~33% on average, resulting in a limited EQE. The *J-V* characteristics presented in Fig. 2b show a short circuit current density of 18.7 mA/cm^2, equivalent to that expected from integrating the EQE measurements with the AM1.5G solar spectrum. The limiting factors are instead the V_{OC}, which is 0.90V (compared to a typical value of ~1.05 – 1.08 V for our GaAs/GaAs structures), and the FF of 0.76, resulting in an efficiency of only ~12.8% without an ARC. We expect efficiencies close to ~18% once a good ARC is deposited on the cell.

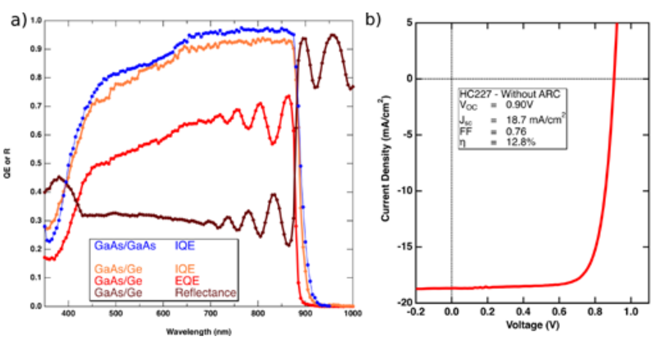

Figure 2. (a) Internal and external QE characteristic, as well as reflectance, of a GaAs heterojunction solar cell grown on a spalled Ge wafer. The IQE of a reference GaAs cell grown on GaAs is included for comparison. (b) JV measurement of the cell grown on spalled Ge, highlighting the relatively high short-circuit current and the limited V_{OC}.

By investigating the dark JV characteristics of the device, we can probe more in detail the causes of this performance (Fig. 3). The cell is dominated by a J_{o2} characteristic current, limiting the performance of the device at 1-Sun illumination. J_{o2} current is typically a result of non-radiative recombination, which happens at structural defects such as anti-phase domains (APDs) and dislocations generated by stress relaxation. Furthermore, the roll-over at V>0.9V is related to a relatively high sheet resistance in the emitter layer (~235 Ω/sq), which increases the series resistance in the device (~3 Ωcm^2).

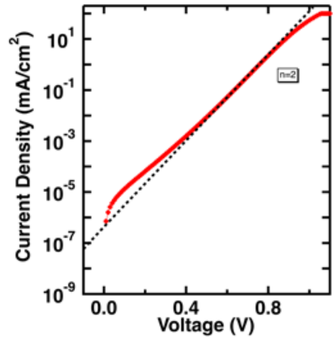

Figure 3. Dark JV characteristics of GaAs heterojunction grown on a spalled Ge wafer, on a logarithmic scale, highlighting the J_{o2}-limited performance of the cell. The dashed lines are used as a guide to the eye.

To investigate further the structural properties of the material, the lattice mismatch was measured by XRD (Fig. 4). The GaAs is mismatched to Ge, as expected, but in particular the InGaP layers exhibit a large tensile strain with respect to the Ge substrate. The mismatch is also reflected in the rough surface morphology, shown in the inset of Fig. 4, a Nomarski image of the top surface of the solar cells.

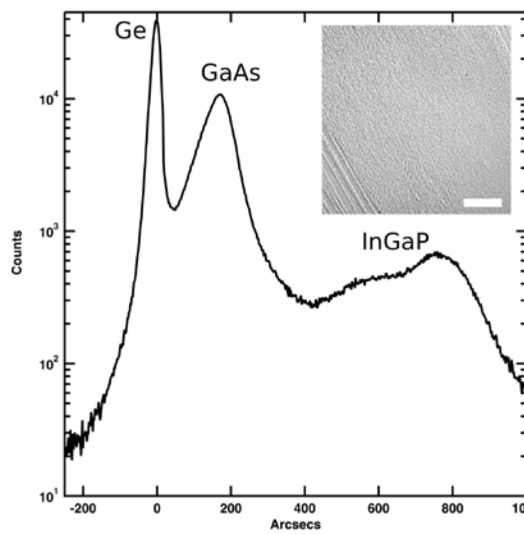

Figure 4. ω-2θ XRD measurements on GaAs solar cells grown on spalled Ge wafer, highlighting the large lattice mismatch between the Ge and the GaAs and, even more pronounced, the InGaP layers. The inset shows an Nomarski image taken at 5x magnification. The scale-bar is 200μm.

We can thus at least partially explain the limited performance as a result of the large lattice mismatch of the InGaP layers. This is expected to lower the efficiency, as it is often related to the presence of structural defects, which would worsen the quality of the various interfaces between the layers and generate dislocations and APDs across the cell. The device issues discussed before also influence the device performance. The unpolished, spalled surface does not appear to be the limiting factor at this stage, even if arrest lines and morphology issues caused by the spalling can reduce the area available for device fabrication. By lattice matching the InGaP to the GaAs and the Ge we expect improved performance, thus approaching the efficiency of HVPE solar cells homo-epitaxially grown on GaAs. Furthermore, we must investigate further the nucleation of epi-layers on Ge, as the growth on both spalled and bulk surfaces is not yet fully optimized. The development of a control sample on non-spalled Ge is in fact paramount for a direct comparison of devices on spalled- and bulk-Ge. However, the work presented here is a first step towards high efficiency solar cells on spalled Ge.

IV. Conclusion

We demonstrate the first GaAs hetero-junction solar cell grown on an unpolished, spalled Ge substrate, with an efficiency of 12.8% without any anti-reflection coating. The IQE is comparable to typical GaAs solar cells grown by HVPE on GaAs, but the FF and the V_{OC} must be improved substantially to achieve high efficiency. A major limitation of the current cell is identified in the substantial lattice mismatch between the Ge substrate and GaAs/InGaP-based device, which is expected to substantially impact the efficiency because of the insurgence of structural defects. At the same time, even if the unpolished surface is not the limiting factor in the performance, growth on spalled Ge must be investigated further. This initial result demonstrates how this approach, combining spalled Ge and growth on an unpolished wafer, is a promising path forward for low-cost, high efficiency solar cells.

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