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High Efficiency GaAs-Ge Tandem Solar Cells Grown by MOCVD

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Introduction

High conversion efficiency and low weight are obviously desirable for solar cells intended for space applications. One promising structure is GaAs on Ge. The advantages of using Ge wafers as substrates include the following:

- high efficiency: by forming a two-junction tandem cell
- low weight: superior strength allows usage of thin (3 mil) wafers
- good substrate for GaAs: is lattice matched, thermal expansion matched, and available as large-area wafers.

Experimental

The cell structure studied in this work is shown schematically in figure 1. The GaAs and GaAlAs layers are grown by metalorganic chemical vapor deposition (MOCVD) in a SPI-MO CVD^{TM} 450 system. This reactor deposits onto five two-inch diameter or three three-inch diameter wafers per run, with a typical thickness uniformity of ±4% over the entire batch. The substrates used in this work are two-inch Ge wafers, 0.008-inch thick, n-type, with a resistivity of 0.014 ohm-cm. The surface preparation before GaAs growth consists of scrubbing the surface with a modified commercial cleanser, etching the wafer in a NH_40H-H_20_2-H_20 mixture, rinsing in deionized water and a final blow dry in filtered N_2. The bottom cell (Ge p-n junction) is formed by in-diffusion of Ga and As from the GaAs layer growth. The As diffuses faster than the Ga, but since Ga has a higher solid solubility at the growth temperature, a p-type Ge top layer is formed. Measured and calculated Ga and As profiles in the Gc are shown in figure 2. The Ge junction profile is controlled by the time-temperature schedule used during growth of the top cell. The basic MOCVD growth parameters used are listed in table 1. The Ge wafers, before being subjected to growth of the GaAs top cell, are

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first coated on the backside with MOCVD-grown GaAs to minimize autodoping effects. The device fabrication tests are listed in table 2, and the cell size used in this work is 2 cm × 2 cm.

Ge Autodoping

The high vapor pressure of Ge causes the vapor transport of Ge atoms from hot, exposed Ge surfaces (typically the back of the wafer) to the growing film. In the MOCVD growth of GaAs on Ge these atoms are incorporated into the GaAs as donors, which can cause major problems by compensating the acceptors in the p-type regions of the cell (emitter, window, and cap layers). A straight-forward solution to this problem is to coat the back of the Ge wafers before growing the cell structure. We have found that a few microns of MOCVD-grown GaAs is an effective coating for this purpose. The results of one of our early studies of this problem are displayed in figure 3. The inset shows a typical Polaron doping profile of autodoped GaAs grown on Ge. The doping level at the GaAs surface is not a function of how thick the grown layer is. This figure shows that the autodoping level for GaAs on Ge is a strong function of growth temperature, but can be reduced dramatically by the GaAs back-side coating.

Solar Cell Results

The efficiency-measurement I-V curve for our best GaAs-Ge cell is shown in figure 4. This measurement was performed at NASA Lewis Research Center through the courtesy of R.E. Hart, Jr. The 1-sun AM0 efficiency value of 21.7% is the highest reported to date for a GaAs-Ge cell and for a two-terminal monolithic tandem cell. The AM1.5 1-sun measurement of this cell at Spire yields an efficiency of 24.3%, and at SERI yields a value of either 24.4% or 20.2% depending on the solar simulator used. These data point out the extreme sensitivity of tandem cell efficiency to the exact spectrum of the incident radiation, and improved methods of testing tandem cells are currently being developed at the national laboratories.

Discussion

To understand the operation of these cells, we first examine the quantum-efficiency curve, figure 5. The data were measured without light or voltage biases. The spectral response is identical to that of a good GaAs cell, with negligible response indicated from the Ge. The Ge cell does not contribute because at wavelengths beyond 870 nm the high-quality GaAs junction is turned off, blocking current generated in the Ge cell. (In cases where the GaAs junction is short-circuited, we do see a long-wavelength response characteristic of Ge). The Ge junction, in contrast, is leaky, as indicated by its low V_{oc} (about 0.2 V), and does not interfere with measurement of the GaAs response. Efforts to measure the Ge response by light-biasing the GaAs cell have not been successful yet, but are continuing. We believe that the Ge cell is in fact generating a large photocurrent, and this accounts for the relatively high measured fill factor. If the GaAs and Ge cells were seriously current-mismatched, then we could not measure both high short circuit current and high fill factor.

We have obtained several types of data showing the existence of a p/n junction in the Ge wafer, supporting our tandem cell hypothesis. These include spreading resistance doping profiles of the Ge, cross-sectional EBIC line scans, and temperature coefficient measurements.

Figures 6 and 7 show doping profiles in the Ge substrate determined by spreading resistance after growth of the GaAs cell. A highly-doped n-type region extends about 6 microns into the Ge substrate, which has a background doping of about $5 \times 10^{17} cm^{-3}$. The n-type doping profile is caused by rapid in-diffusion of arsenic during growth of the GaAs cell. A more detailed look at the profile near the GaAs interface (figure 7) reveals a very shallow but clear p-n junction in the Ge. As explained earlier, the p-type doping is from diffusion of Ga, which over-dopes the n-type As profile. This is the most direct evidence possible of a Ge p-n junction.

We have also detected the positions of the GaAs and Ge junctions by Electron Beam Induced Current (EBIC) line scans of cross-sectioned cells. Figure 8 shows such a line scan superimposed on a simple diagram of the sample. The two peaks in the EBIC scan correspond to the GaAs and Ge junctions. From the scale on the original micrograph, these occur at depths below the surface of about 0.7 and 6.2 microns respectively. (Note that the junction depth is about 0.2 microns shallower in the finished cell of figure 8 compared to the as-grown material of figures 6 and 7, due to removal of the GaAs contact layer and addition of the antireflection coating). This data would indicate a junction depth within the Ge of about 1 micron, larger than what was obtained from spreading resistance. At this time we do not understand the discrepancy. However, the important point is that we do see a second junction within the Ge wafer by both techniques. As a point of interest, it was necessary to forward bias the cell to 775 mV in order to detect the Ge response. This is the same problem encountered in the quantum efficiency measurement: unless the GaAs junction is turned on, its high resistance blocks current generated in the Ge.

Temperature coefficient measurements made at SERI also imply a GaAs/Ge tandem. Table 3 summarizes the temperature coefficients of efficiency, V_{oc}, I_{sc}, and FF from 10 to 80°C. Data are shown for the GaAs/Ge cell of figure 1 and for a GaAs/GaAs control cell. The temperature coefficient of the GaAs/Ge cell is more than twice that of the the GaAs cell, because Ge, with its small band gap, is much more temperature sensitive than GaAs. The V_{oc} values extrapolated to zero Kelvin are 1.519 V for the GaAs cell and 2.299 V for the GaAs/Ge cell. The difference is roughly the band gap of Ge, again as expected for a series tandem.

Given that we have a series-connected monolithic tandem cell of GaAs and Ge, it is somewhat surprising that the tandem does not appear to be seriously current-limited by the Ge subcell. An earlier report of a mechanically-stacked tandem achieved only 7.86 mA/cm^2 from the Ge cell at AM1.5 [ref.1]. However, our calculations show that if all light absorbed in a single pass were collected in the Ge, a maximum one-sun AM0 photocurrent of 38.7 mA/cm^2 (at 25°C and 39.7 mA/cm^2 at 75°C) is possible under a GaAs filter. The fact that our best cells are not current limited implies very good collection in the Ge subcell (or a very red-rich simulator).

We have seen indications of Ge current-limiting in some cells, particularly under AM1.5 measurement conditions. The reason is the infrared absorption bands in the AM1.5 spectrum, which do not affect the GaAs cell but reduce the current of the Ge cell. Figure 9 shows the efficiency curves of the same cell measured on two different simulators at SERI. The V_{oc} and J_{sc} are nearly identical, but the fill factors are very different. The curve with the dent in the knee is for the simulator with less infrared light, giving a lower Ge photocurrent. The reason that I_{sc} is not affected is that the Ge cell is leaky, and breaks down at very low reverse voltages. Even though the Ge cell is driven into reverse bias by the current mismatch, it causes little voltage loss.

To summarize our understanding of the high-efficiency GaAs/Ge cell, a p-n junction is created in the Ge substrate as part of the GaAs cell growth process. This junction is in series with the GaAs junction, creating a monolithic tandem structure. The Ge junction is leaky enough in the reverse direction that it does not limit the short-circuit current of the series-connected tandem. However, it can limit the fill factor if the short-circuit current of the Ge subcell is too low. Finally, since the polarities of the GaAs and Ge junctions are the same, their open circuit voltages add.

Summary

A 4 cm^2 GaAs-Ge two-terminal monolithic tandem cell grown by MOCVD has demonstrated 21.7% efficiency measured at NASA (1-sun, AM0) and 24.3% measured at Spire (1-sun, AM1.5). The existence of a p-n junction in the Ge has been confirmed by spreading resistance probe, EBIC, and temperature coefficient data, and is explained by the diffusion properties of Ga and As in Ge. The top cell-bottom cell interconnect is accomplished by the GaAs-Ge tunnel junction which appears to be adequate for one-sun operation. The testing methodology for determining the absolute efficiency of two-terminal tandem cells needs improvement. Finally, the use of Ge substrates has been shown to be a viable route to achieving high-efficiency solar cells for space applications.

Reference

[1] L.D. Partain, M.S. Kuryla, R.E. Weiss, R.A. Ransom, P.S. McLeod, L.M. Fraas and J.A. Cape, "26.1% Solar Cell Efficiency for Ge Mechanically Stacked Under GaAs," J. Appl. Phys., **62**, pp. 3010-3015, 1987.

Table 1. Growth Parameters

Sources:	TMGa, TMAl, AsH_3
Dopants:	SiH_4 (N) DMZn (P)
Pressure:	1 atm.
Main Flow:	5 slpm H_2
Growth Rate:	4 μm/hr
Temperature:	700°C
V-III Ratio:	15:1

Table 2. Process Sequence for GaAs-Ge Solar Cell

1.	Remove GaAs Back Coating
2.	Evaporate Back Contact (AuAg)
3.	Alloy Back Contact
4.	Image-reversal Photolithography for Front Grid
5.	Evaporate Front Grid (CrAuAg)
6.	Liftoff
7.	Sinter Contacts
8.	Plate Metal (Au)
9.	Photolithography for Mesa Etch
10.	Mesa Etch
11.	Selective Etch to Remove GaAs Cap
12.	Evaporate AR coating (ZnS + MgF_2)

Table 3. Temperature Coefficients (ppm/deg C) of Efficiency, V_{oc}, I_{sc}, and FF Measured for GaAs/Ge and GaAs/GaAs solar Cells

Parameter	GaAs/Ge	GaAs/GaAs
V_{oc}	-3702	-1669
I_{sc}	+ 445	+ 246
FF	- 175	- 29
Eff	-3067	-1466

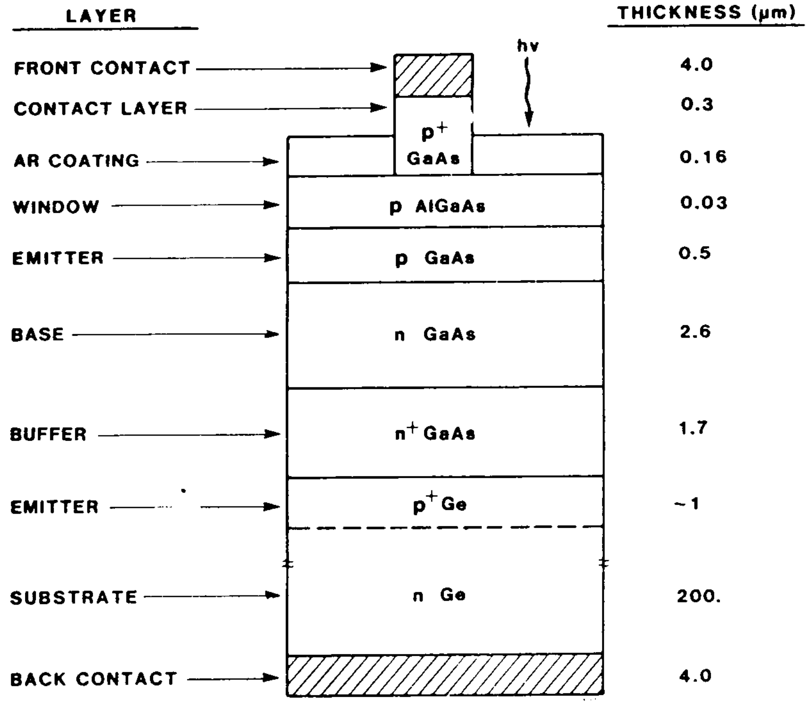


Figure 1. Structure of GaAs-Ge Tandem Solar Cell

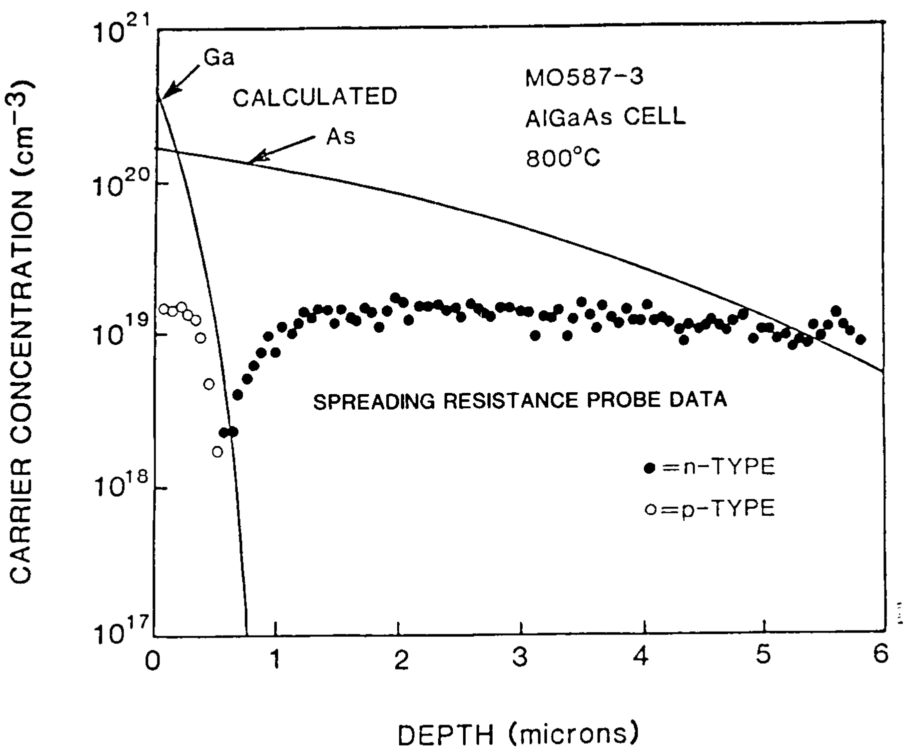


Figure 2. Doping Profile in a Ge Substrate after Growth of an AlGaAs Solar Cell at 800°C.

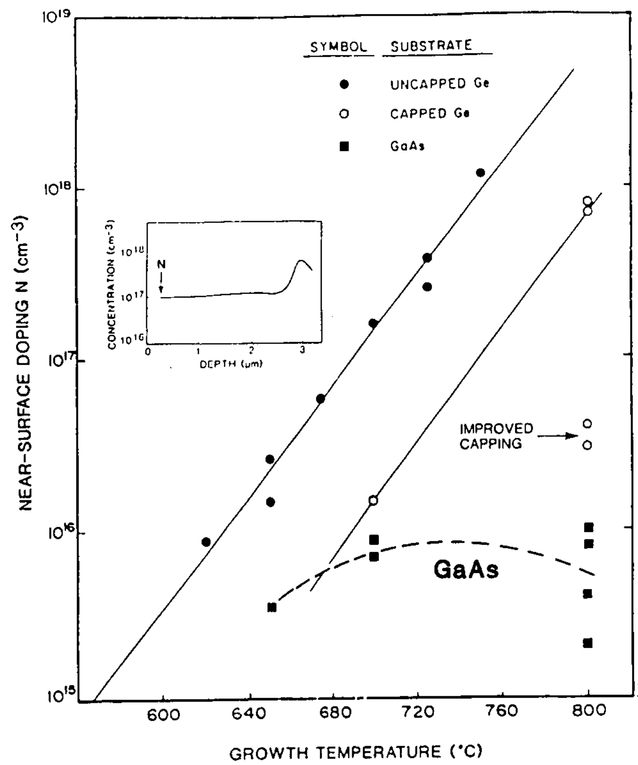


Figure 3. Autodoping of GaAs from Ge Substrate.

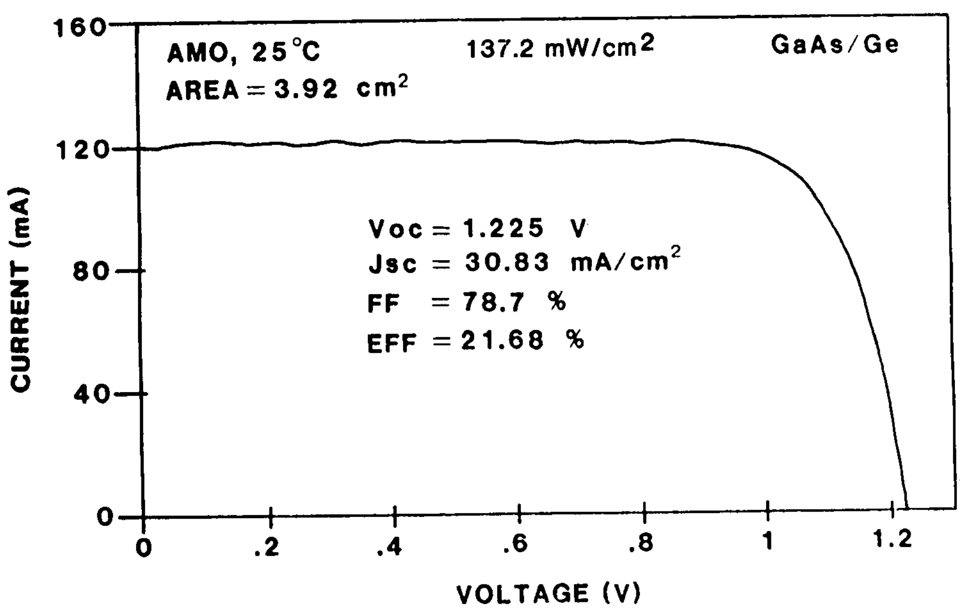


Figure 4. GaAs-Ge Tandem Cell Efficiency Measurement at NASA-Lewis.

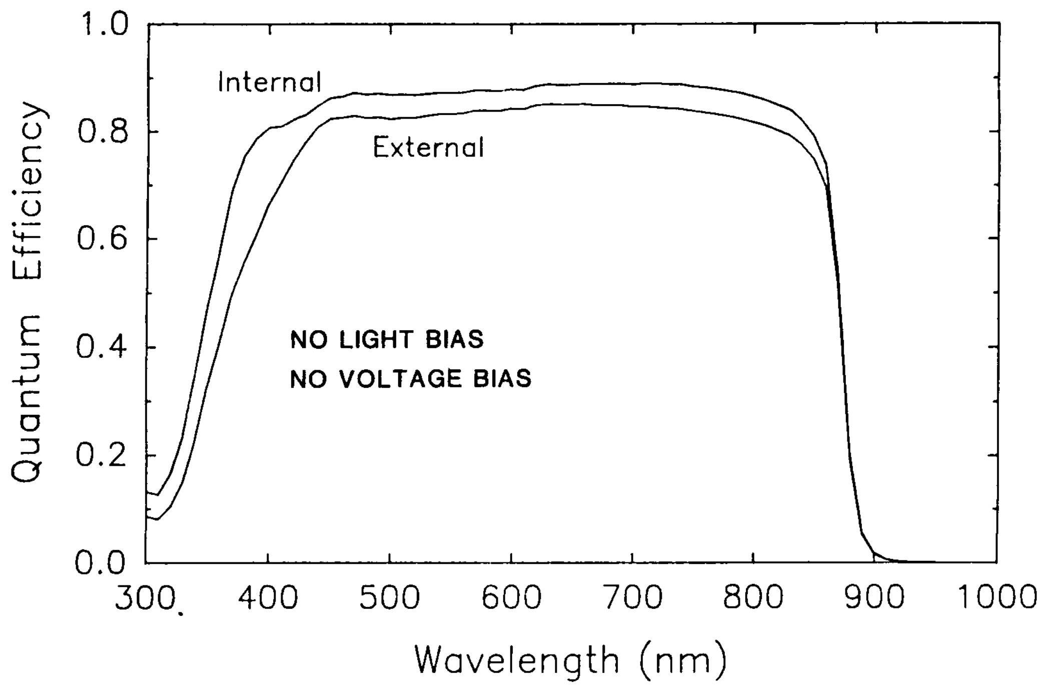


Figure 5. Measured Spectral Response of GaAs-Ge Tandem Cell.

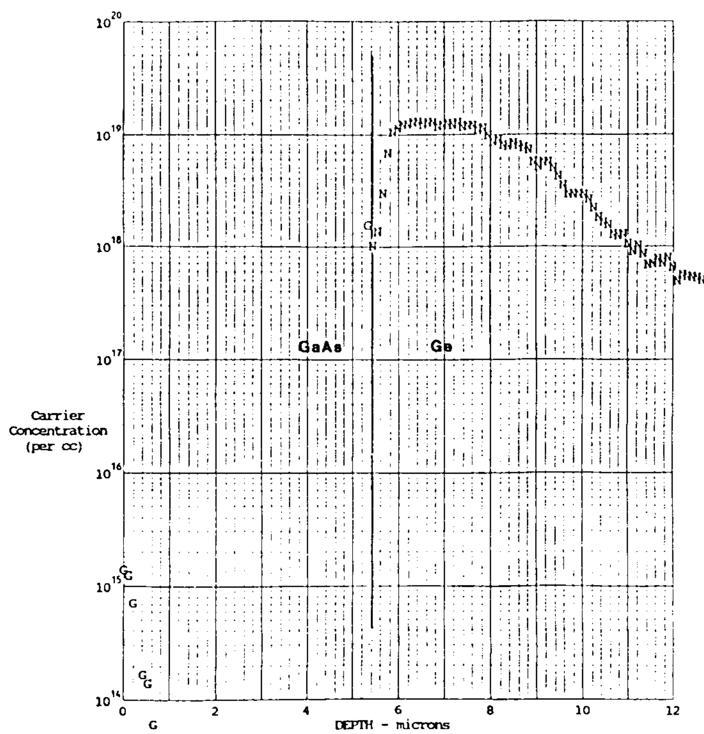


Figure 6. Doping Profile of the Ge Substrate after Growth of a GaAs solar Cell, Obtained by Spreading Resistance. The heavy n-type doping is caused by in-diffusion of arsenic from the GaAs.

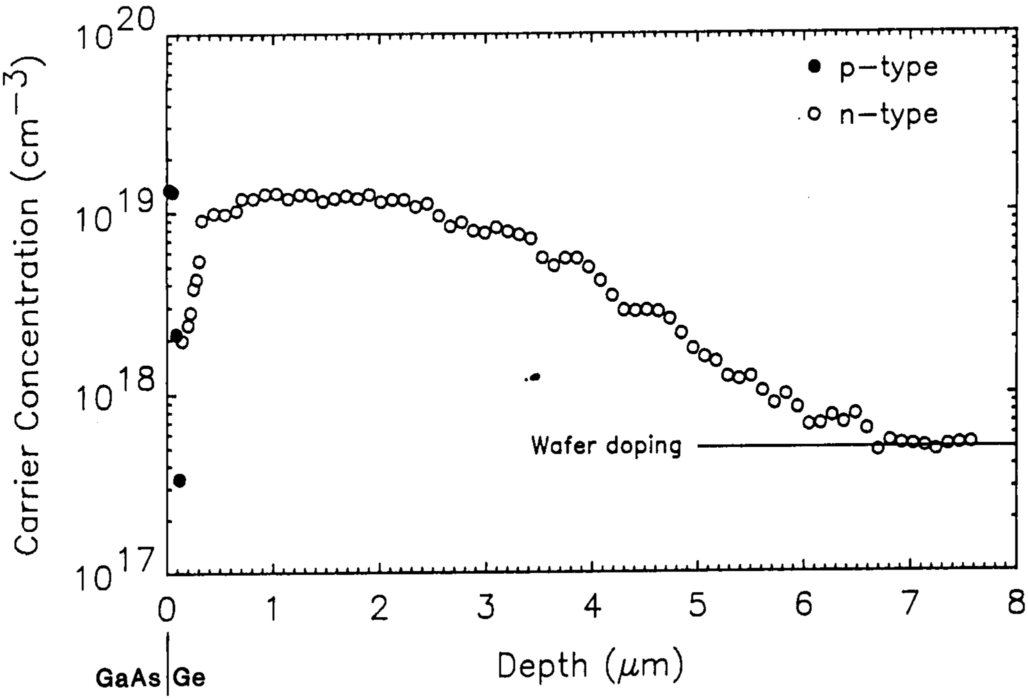
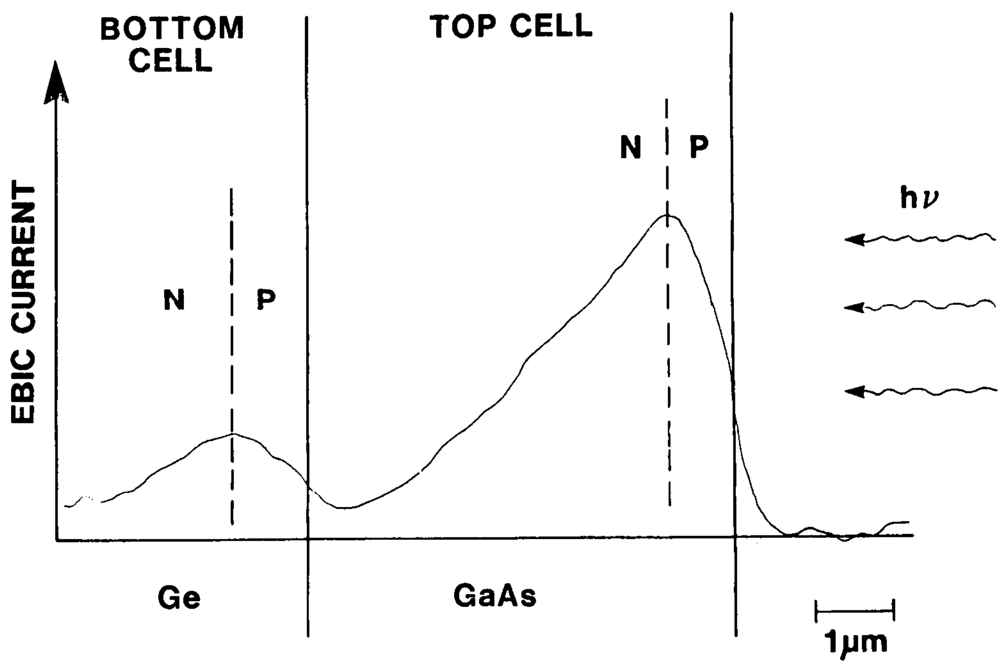


Figure 7. Spreading Resistance Probe Profile of Ge Bottom Cell.



MEASUREMENT COURTESY OF R. MATSON, SERI

Figure 8. EBIC Line Scan on Cross-Section of GaAs-Ge Tandem Cell.

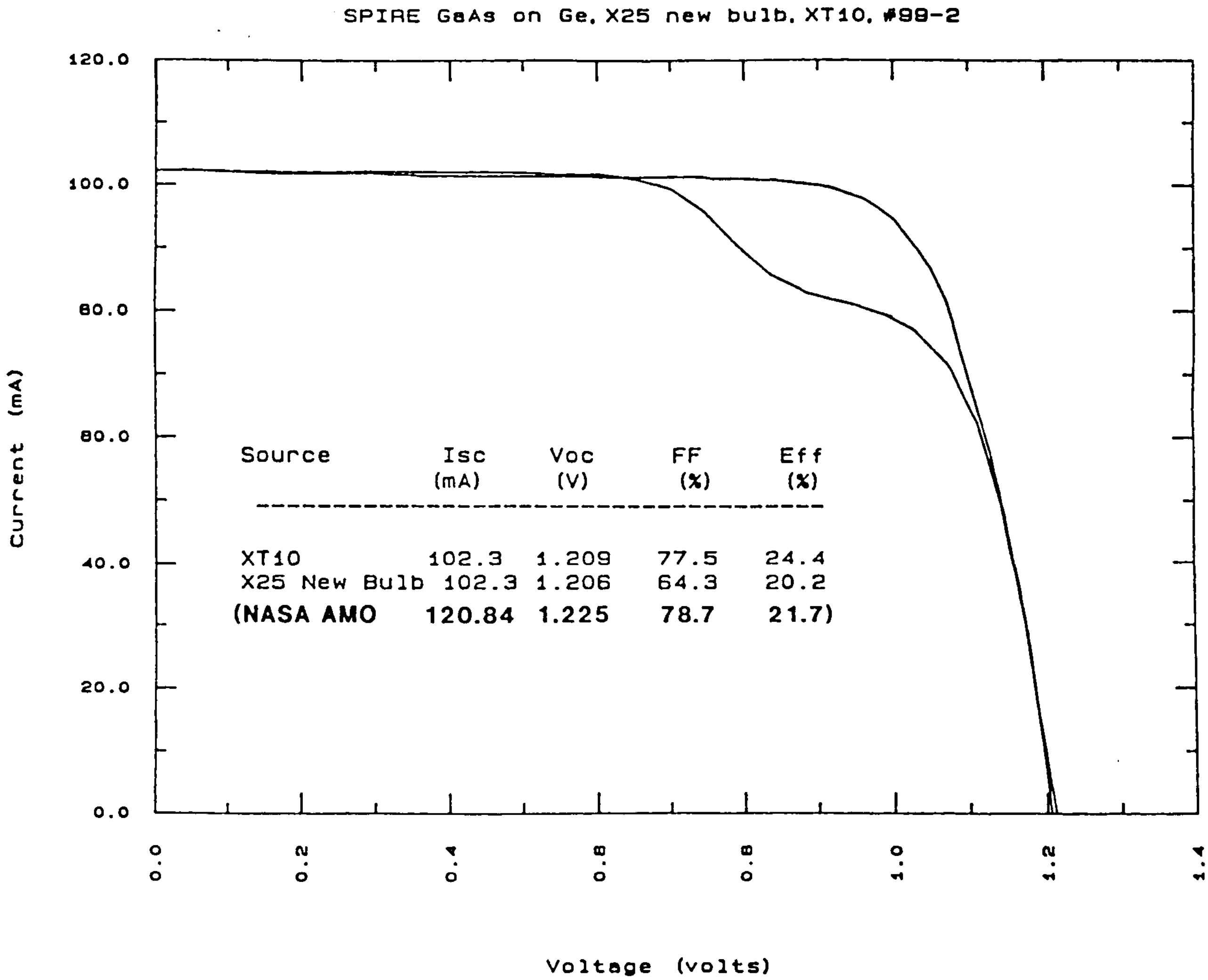


Figure 9. AM1.5 Efficiency Curves of a GaAs/Ge Solar Cell Measured on Two Different Simulators at SERI.