RUSSIAN ACTIVITIES IN SPACE PHOTOVOLTAIC POWER MODULES WITH CONCENTRATORS[1]

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Abstract

Space concentrator modules with point- and line-focus Fresnel lenses and with reflective parabolic troughs have been developed recently at Ioffe Physico-Technical Institute. PV receivers for these modules are based: on the single junction LPE and MOCVD AlGaAs/GaAs solar cells characterized by AM0 efficiencies of 23.5-24% at 20-50 suns and 24-24.7% at 50-200 suns; on the mechanically stacked tandem AlGaAs/GaAs-GaSb cells with efficiency of 27-28% at 20-100 suns. MOCVD AlGaAs/GaAs cells with internal Bragg reflector have shown a higher radiation resistance as compared to a traditional structure. Monolithic two-terminal tandems AlGaAs (top)-GaAs (bottom) for space application and GaSb (top) - InGaAsSb (bottom) for TPV application are under development as well.

Introduction

Concentrator concept in space provides potentially higher PV conversion efficiency and inherent protection from radiation effects at reduced cost. Optimal III-V materials and their combinations can be used for fabrication of the solar cells in this case to obtain the best output parameters of the PV modules. As to the sunlight concentrators for these modules, so they can be based on the refractive or reflective optical elements. An attractive feature of the refractive concentrator approach is a more "natural" module design. Here solar cells are placed on the bottom plate of the module which at the same time serves as a heat sink. A potential advantage of the reflective concentrator approach is an extremely high optical efficiency (if silver coating is used) and better radiation stability. That is why both these approaches are under development at the Ioffe Institute.

Solar Cells

The first heterostructure solar cells based on AlGaAs system were developed at Ioffe Physico-Technical Institute in 1969-1970 [1,2]. LPE method was used to grow those heterostructures. Many efforts had been done in the field of LPE technique, so that LPE is known to be a relatively inexpensive and effective method for production of the single-junction AlGaAs/GaAs SCs. LPE method have shown up to now the best crystal quality parameters of the epitaxial AlGaAs layers realized with more or less simple equipment.

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Last years low-temperature LPE had been promoted successfully at Ioffe Institute in respect to fabrication of multilayer AlGaAs/GaAs SCs [3]. In particular, the crystallization rates of high quality layers as low as 0.1-1 nm/s in temperature range 550-400 C had been demonstrated - the rates of the same order of magnitude as in MBE and MOCVD. Both free electrons and free holes concentrations can be varied in epitaxial layers within a wide range. That is why LPE can be used for the growth of the monolithic tandem AlGaAs (top)-GaAs (bottom) SC heterostructures with tunnel junction. In the case when AlGaAs-layers are not photoactive, for example, in the case of the single-junction AlGaAs/GaAs SCs with internal Bragg reflector, MOCVD method is used successfully by us for the heterostructure growth.

An alternative to the monolithic tandems is a mechanical stack of two individual SCs, for instance, based on GaAs and GaSb materials [4]. This approach is under development at Ioffe Institute as well. A simple Zn diffusion method is used for GaSb subcell fabrication. At the same time narrow-gap monolithic two-terminal tandems GaSb (top) - InGaAsSb (bottom) could give an increase in net efficiency for space and especially for TPV applications. Such heterostructures are grown by LPE method.

Module Design And Fabrication

Two types of concentrator modules have been designed and manufactured for flight experiments. The first one is based on 4x4 Fresnel lens panel [5] (see Figure 1) and the second is based on the reflective parabolic troughs [6] (see Figure 2). An optical efficiency of 93% for parabolic trough concentrators has been achieved and misorientation curves suitable for space application have been realized in these modules. Diamond-like carbon layers provided an effective corrosion protection of the Ag-coatings of the mirrors: no reduction of the optical efficiency was measured in parabolic trough mirrors during 15 months of their usage in the ordinary indoor conditions. AM0 power density value of 230-235 W/m^2 and specific power 70-75W/kg have been predicted in the arrays based on developed parabolic trough concentrators and linear receivers. Also, the module with ENTECH linear Fresnel lens as a solar concentrator [4] has been developed and measured [7] (see Figure 3). In the latter case the secondary optical elements - quartz cylindrical lenses have been introduced on the front surfaces of the 4x4 mm solar cells. These elements are characterized by a very high optical efficiency providing an additional radiation resistance, 1.5x increased concentration ratio and more wide misorientation range (see Figure 4).

High efficiency (23.4-24.7%, AM0, 20-100 suns) single junction AlGaAs/GaAs solar cells (see Figures 5 and 6) have been designed and manufactured for the modules with concentrators (parabolic troughs and Fresnel lenses). Linear receivers (see Figure 3) with an efficiency of 18.5-19% have been manufactured on the basis of the radiation stable solar cells with internal Bragg reflector. The employment of the Bragg reflector allowed us to increase the internal quantum yield in the long-wavelength range of the spectrum and to use a thinner *n*-GaAs base layer. Radiation resistance under 1 MeV and 3.75 MeV irradiation was increased in these cells owing to an improvement in the radiation stability of the long-wavelength spectral response (see Figures 7 and 8). Mechanically stacked GaAs-GaSb tandem cells with an efficiency of 28-29% at 100 suns have been fabricated for the linear receivers as well.

Advanced Cells and TPV Devices

The heterostructure AlGaAs/GaAs cells with extremely thin both AlGaAs window layer (4-5 nm) and GaAs surface layer (2-3 nm) have been proposed and developed [8] regarding to improvement the cell ultraviolet sensitivity and especially for operation as the betavoltaic cells. In such a device the surface built-in electric field, which, in fact, reduces the height of the protective barrier in a very thin AlGaAs window layer, is accumulated in a heavily doped transparent enough GaAs front layer. This provides a suppression of the fundamental loss mechanism consisting in the tunnelling of the generated hot electrons from absorbing p-GaAs region to the surface states through or over the surface AlGaAs barrier.

Monolithic two-terminal two-junction $Al_{0.35}Ga_{0.65}As$/GaAs solar cells (see Figure 9) have been designed and manufactured by low-temperature LPE. Connecting tunnel diode (see Figure 10) was prepared by LPE method for the first time providing n-type (Te) and p-type (Ge) dopant concentrations as high as $10^{20}cm^{-3}$. Figure 11 shows the spectral response curves for such a tandem cell. The following parameters have been achieved in one of the best samples: V_{OC}=2.53 V, FF=0.81 at 50 suns (AM0, 25°C; see Figure 12). Current densities under one sun AM0 illumination correspond to 15.3 mA/cm² in the GaAs subcell and 14.2 mA/cm² in the $Al_{0.35}Ga_{0.65}As$ subcell. The combination of high sensitivities of both AlGaAs and GaAs subcells in one tandem cell will allow us to achieve the efficiency values comparable with those obtained in InGaP-GaAs monolithic tandem solar cells.

Thermophotovoltaic devices based on GaSb and InGaAsSb have been fabricated by LPE and Zn diffusion methods. The maximum efficiency of 11.3% was measured in GaSb cells under 70 suns AM0 illumination (no GaAs filter). 1 sun AM0 current density of 45 mA/cm² and V_{OC}=0.46V at 3.15 A/cm² have been achieved in these cells. Lattice matched $In_xGa_{1-x}As_ySb_{1-y}$/GaSb heterostructures were grown by LPE from a Sb-riched melt. Band-gap energy of InGaAsSb cells was in the range 0.52-0.6 eV, which provides a long-wavelength edge of photosensitivity of 2150-2350 nm in TPV devices.

Monolithic two-terminal tandem GaSb-InGaAsSb (E_g=0.56 eV) thermophotovoltaic devices with connecting tunnel GaSb diode have been developed and fabricated (see Figures 13 and 14). Theoretical studies have indicated that current matching the top (GaSb) and bottom (InGaAsSb) subcells in tandem TPV devices can be reached in the case of bottom subcell band-gap energies 0.6-0.55 eV for the black-body emitter temperatures of 1100-1500°C, respectively. External quantum yields as high as 80% in the wavelength range 800-1600 nm (top cell) and about 75% in the range 1800-2100 nm (bottom cell) have been measured in tandem cells (see Figure 15). The magnitudes of the V_{OC}=0.61 V and FF=0.75 have been achieved in one of the tandem TPV devices characterized by a high photoresponse up to wavelength of 2150 nm.

Radiation Resistance Results

1 MeV, 2 MeV and 3.75 MeV electron and 6.7 MeV proton irradiation tests have been carried out on AlGaAs/GaAs, GaSb, InGaAs and InGaAsSb cells. GaAs-based cells with the junction depth of 0.4-0.5 μm are characterized by a good radiation resistance, comparable to the best published data [9,10]. GaSb- and InGaAs-based cells have shown radiation resistance similar to the ordinary GaAs-based cells. An improvement in radiation resistance has been achieved in AlGaAs/GaAs solar cells with internal Bragg reflector. In particular, a high stability of the long-wavelength part of the spectral response curve took place even after 3.75 MeV irradiation with the electron fluence of $10^{16}cm^{-2}$ (see Figure 7). This result has been obtained owing to reduction of the photoactive *n*-GaAs base layer thickness up to 1.5 μm when the *p-n* junction depth was in the range of 0.3-0.4μm. $Al_{0.35}Ga_{0.65}As$-based top cells in tandems have also demonstrated the higher radiation resistance, than in ordinary GaAs based solar cells.

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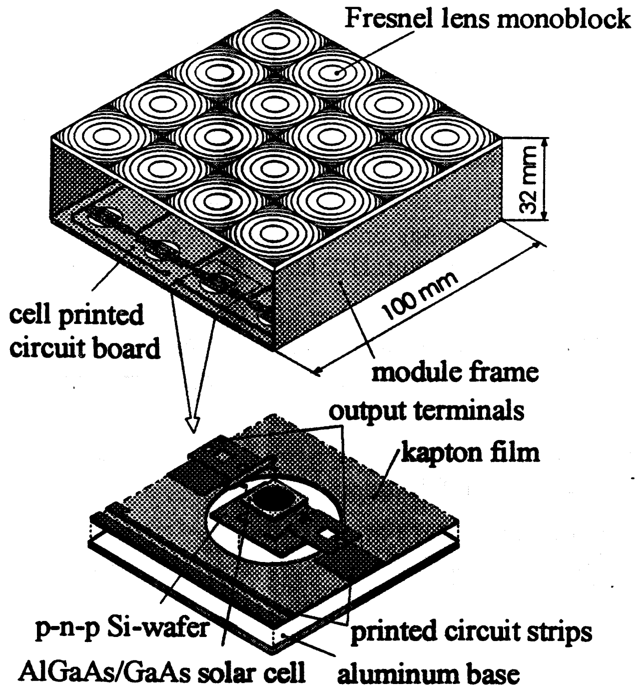


Fig.1. Point-focus Fresnel lens panel PV module conceptual design.

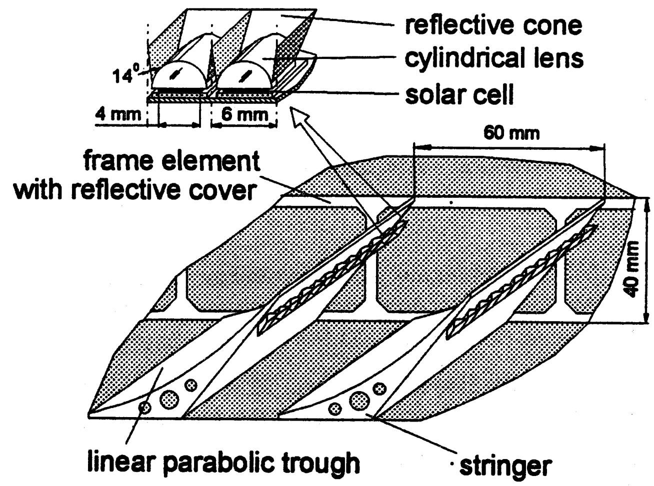


Fig.2. Conceptual design of a concentrator array with linear parabolic troughs.

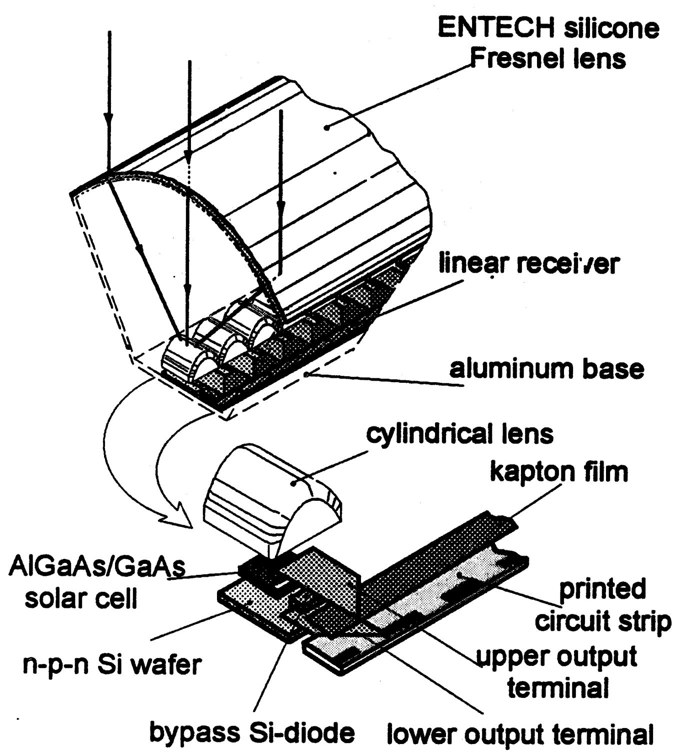
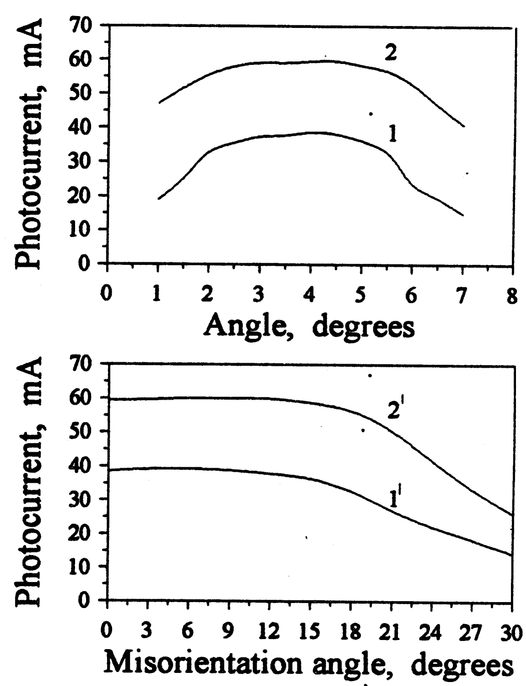


Fig.3. Line-focus Fresnel lens PV module conceptual design. Linear receiver is shown as well.



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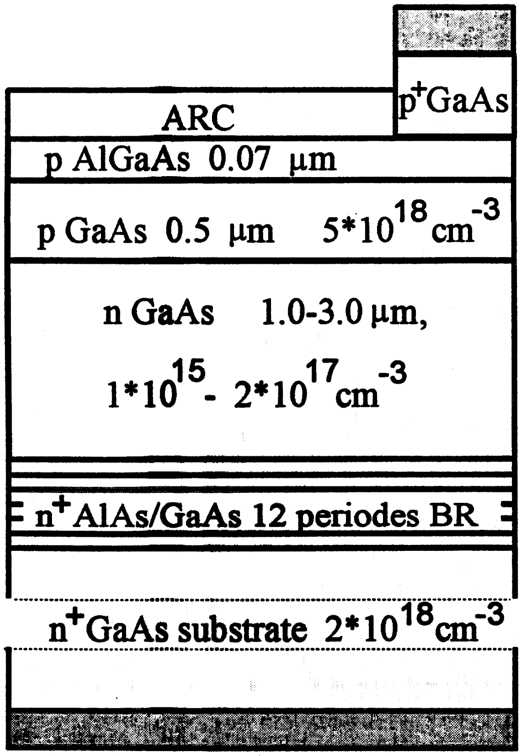


Fig.5. Schematic structure of the solar cell with Bragg reflector (BR).

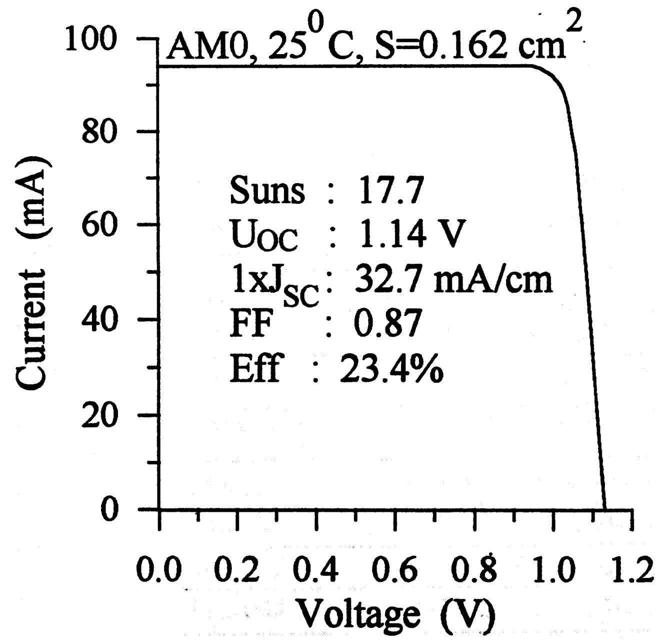


Fig.6. I-V curve of a 23.4% efficient solar cell with Bragg reflector.

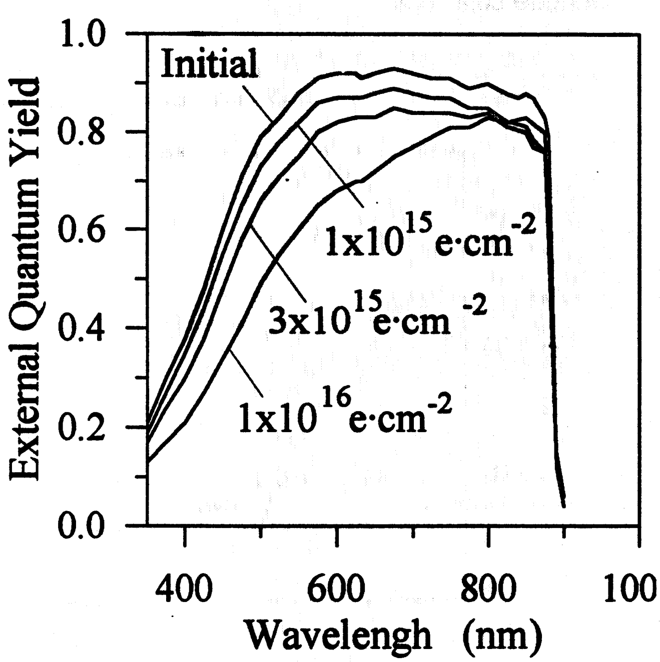
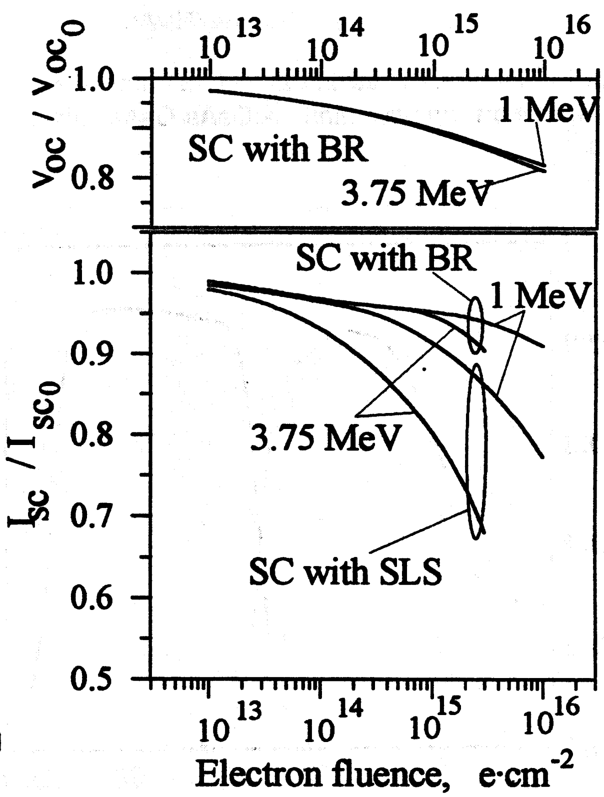


Fig.7. External quantum yield of the SC with Bragg reflector as a function of 3.75 MeV electron fluence.



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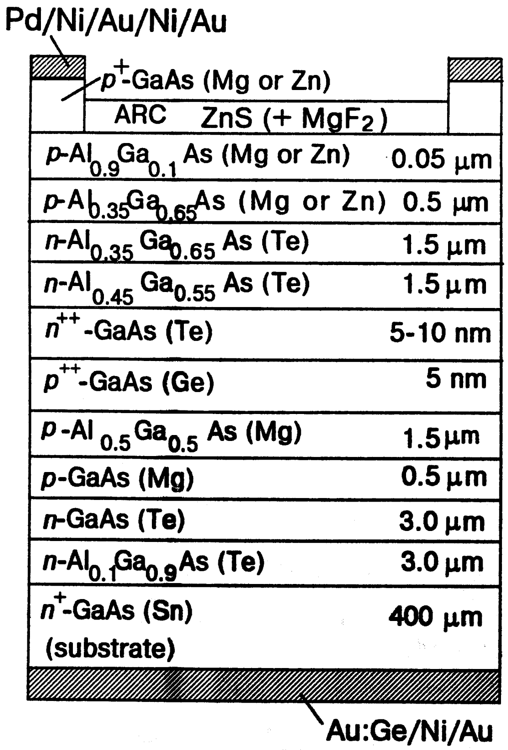


Fig.9. Schematic structure of a monolithic two-junction two-terminal AlGaAs-GaAs solar cell.

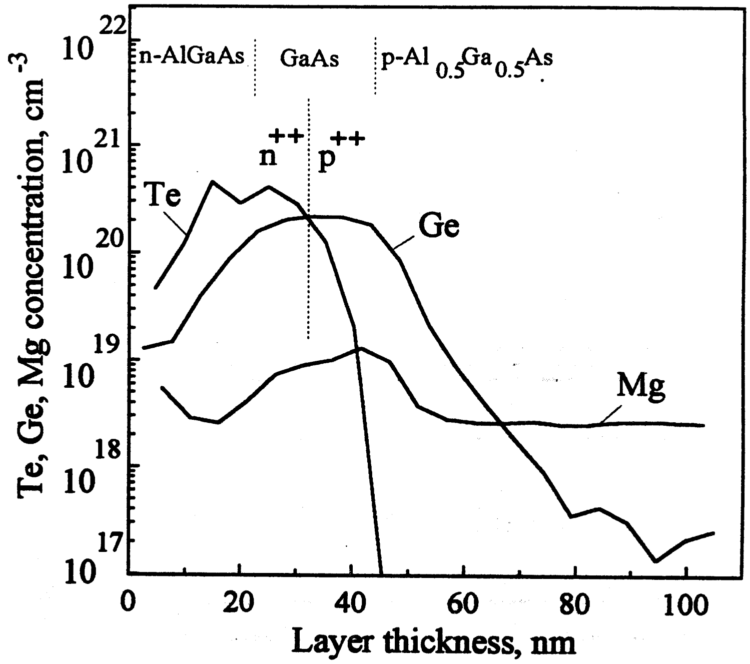


Fig.10. SIMS profiles of dopant elements across the tunnel junction layers in the AlGaAs-GaAs cascade solar cells.

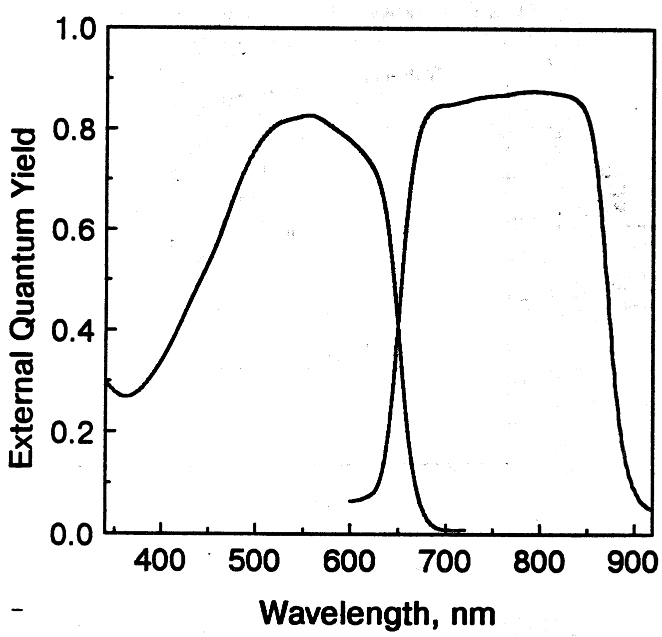


Fig.11. Spectral responses of the AlGaAs- and GaAs-subcell in two-terminal tandem solar cells.

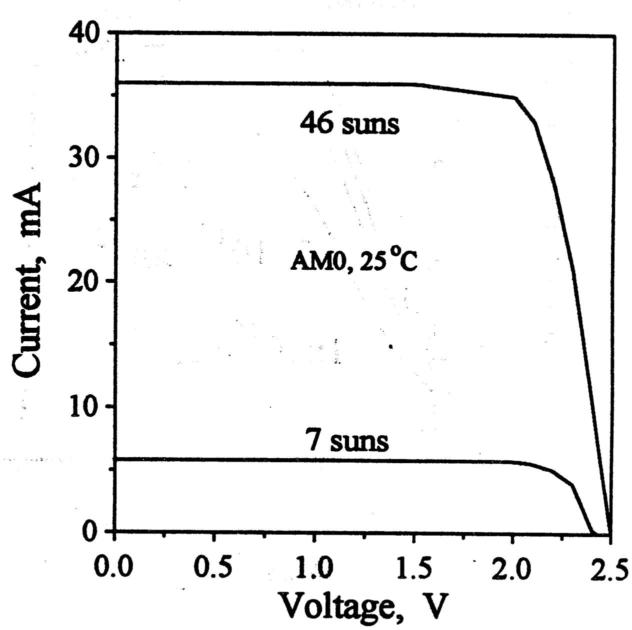


Fig.12. Illuminated I-V characteristics of the AlGaAs-GaAs two-terminal cascade solar cell.

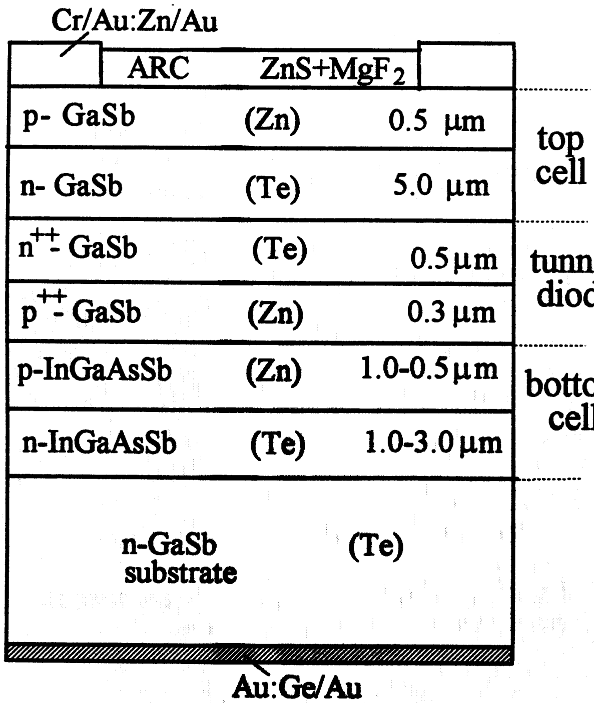


Fig.13. Schematic diagram of the monolithic two-junction two-terminal GaSb-InGaAsSb solar cell.

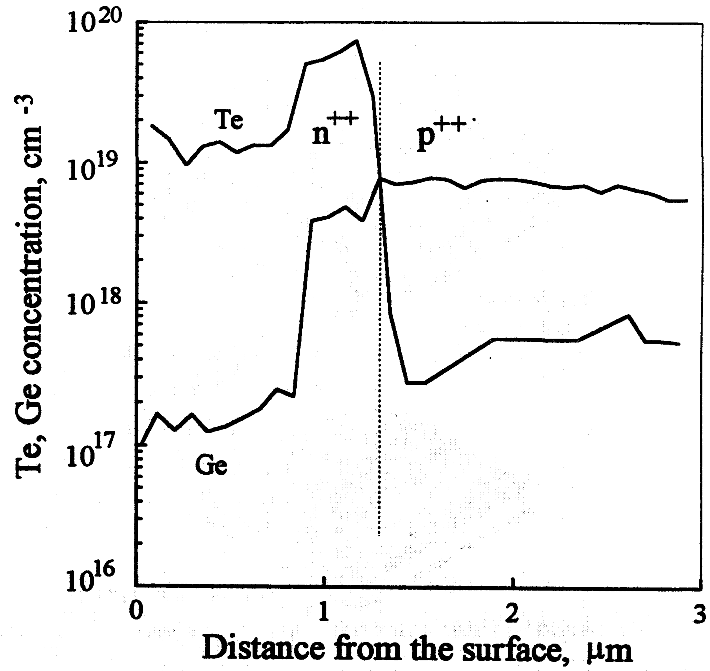


Fig.14. SIMS profiles for Te and Ge dopants in the GaSb-based tunnel diodes for GaSb-InGaAsSb tandem TPV device.

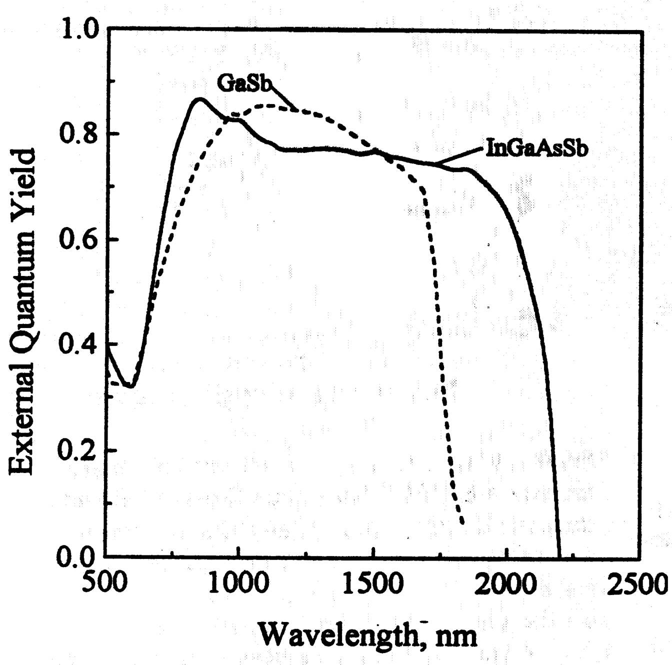


Fig.15. Spectral responses of GaSb- and InGaAsSb-based solar cells with $ZnS+MgF_2$ antireflection coating.

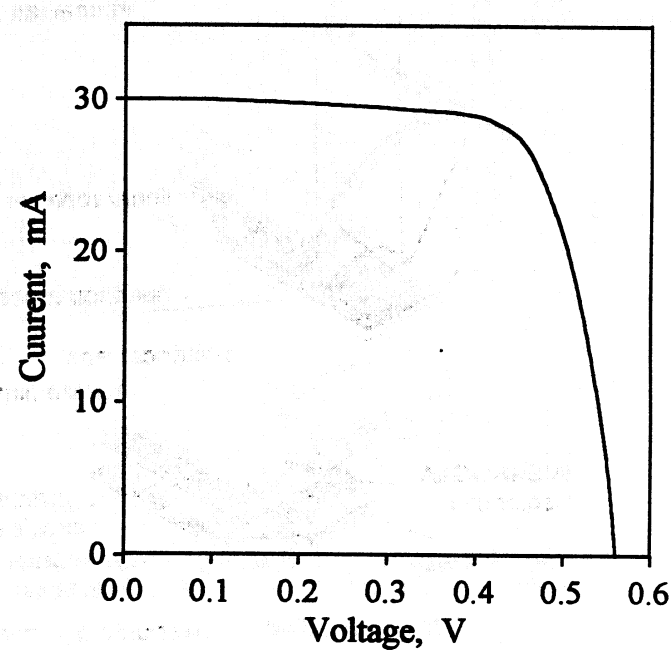
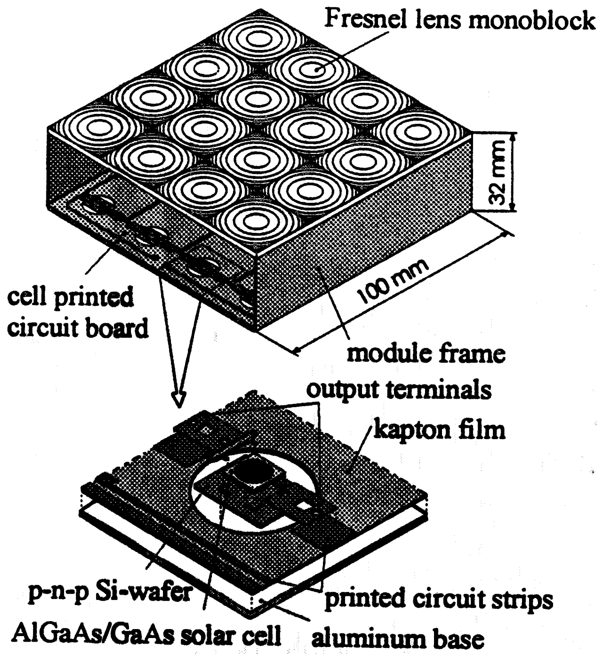


Fig.16. Illuminated I-V characteristic of the tandem GaSb-InGaAsSb (E_g=0.56 eV) TPV device.



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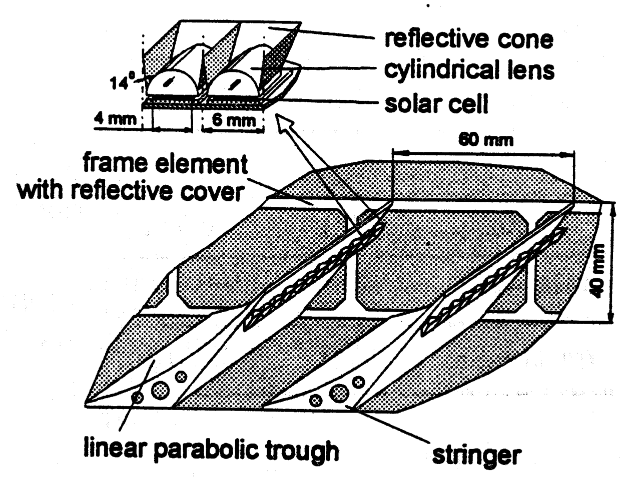

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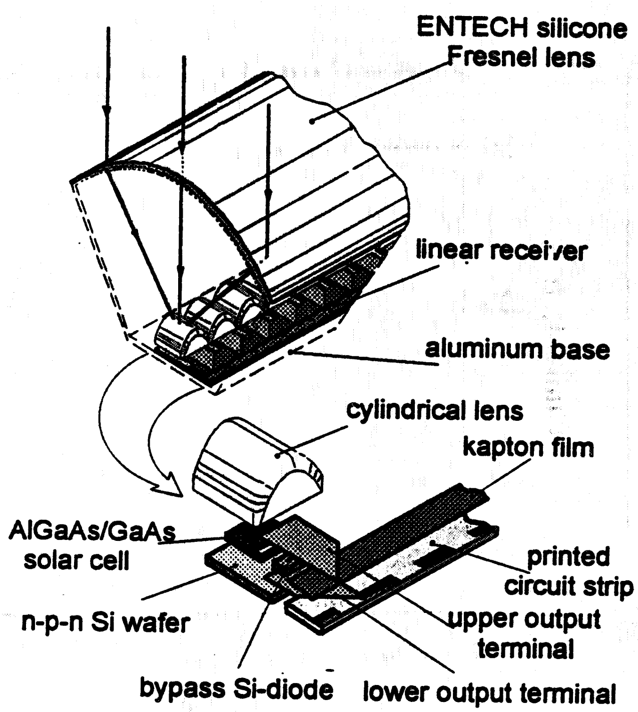
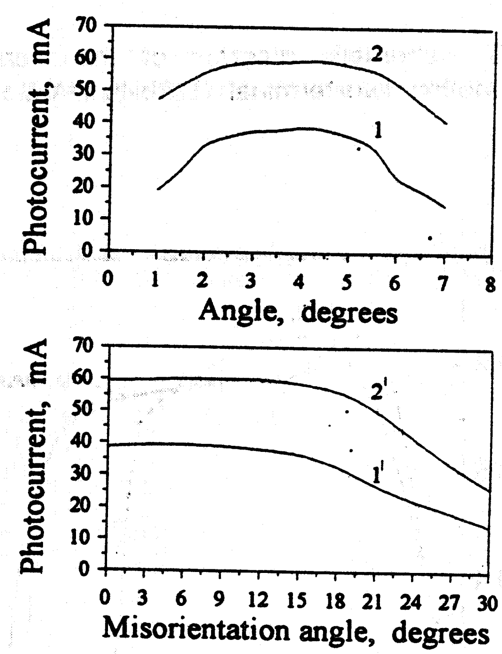


Fig.3. Line-focus Fresnel lens PV module conceptual design. Linear receiver is shown as well.



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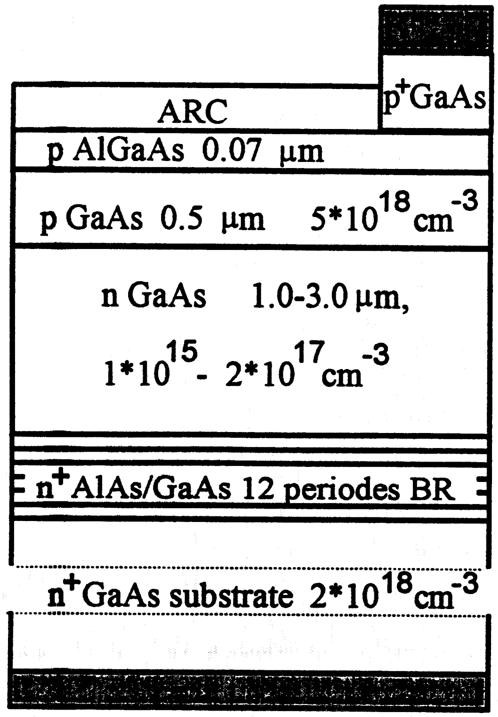

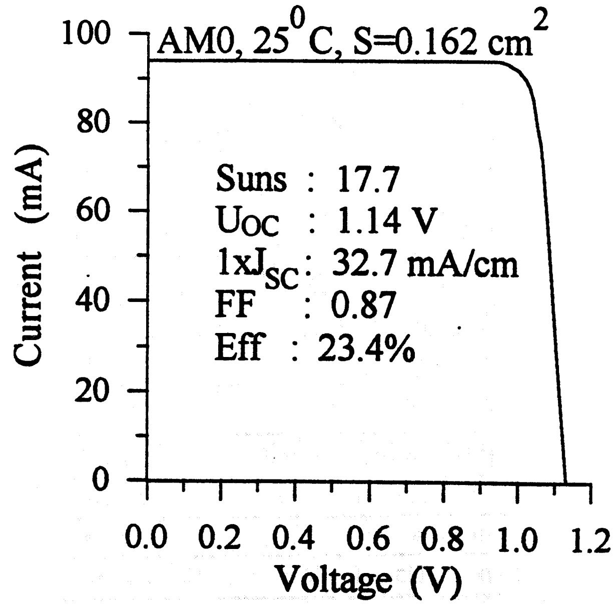

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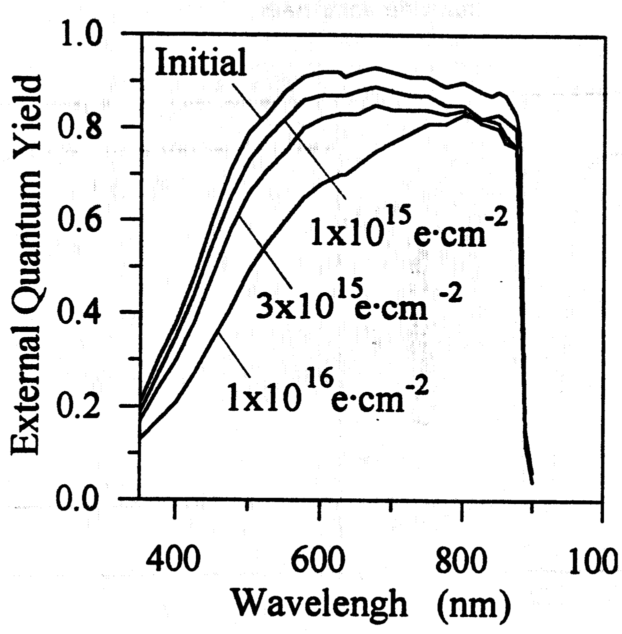

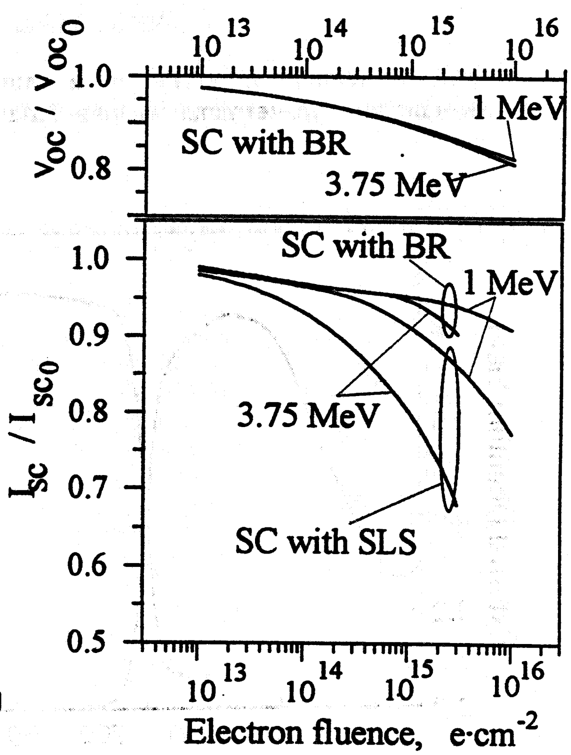

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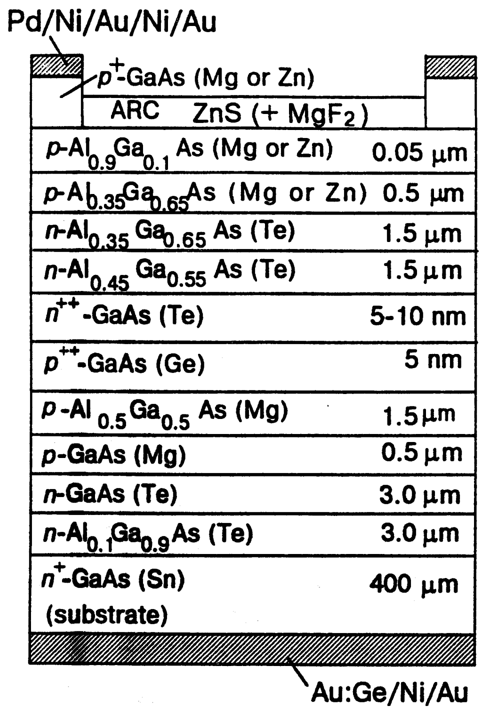

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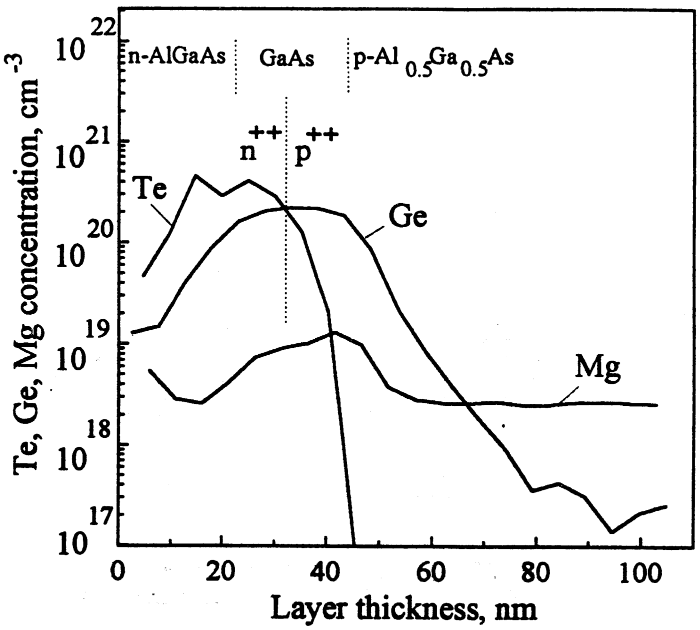

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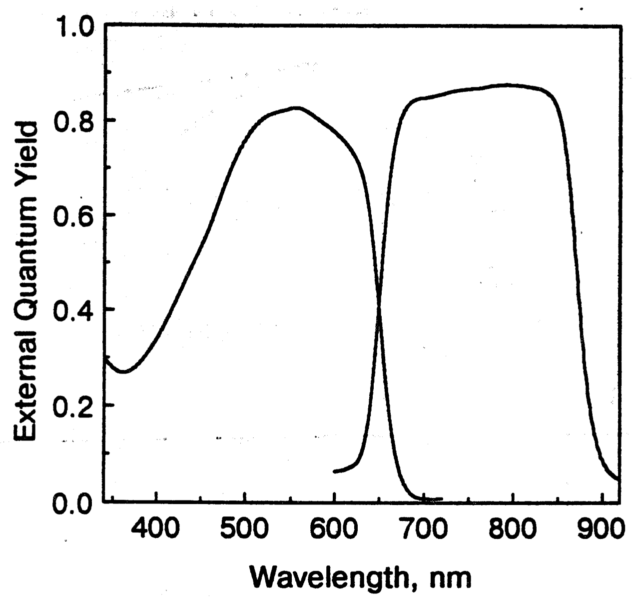

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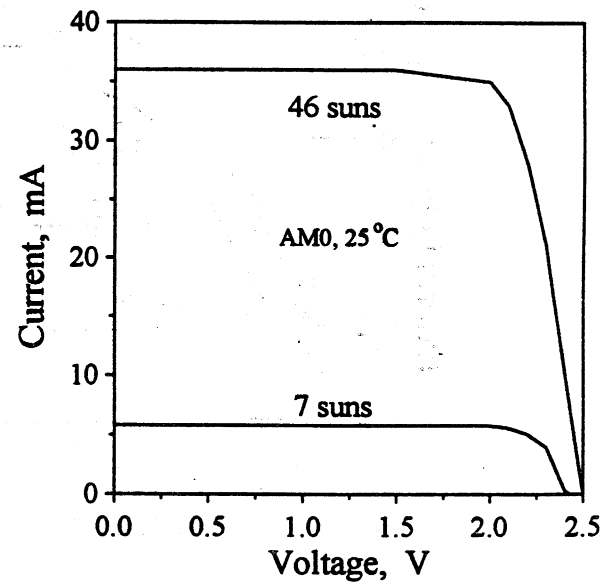

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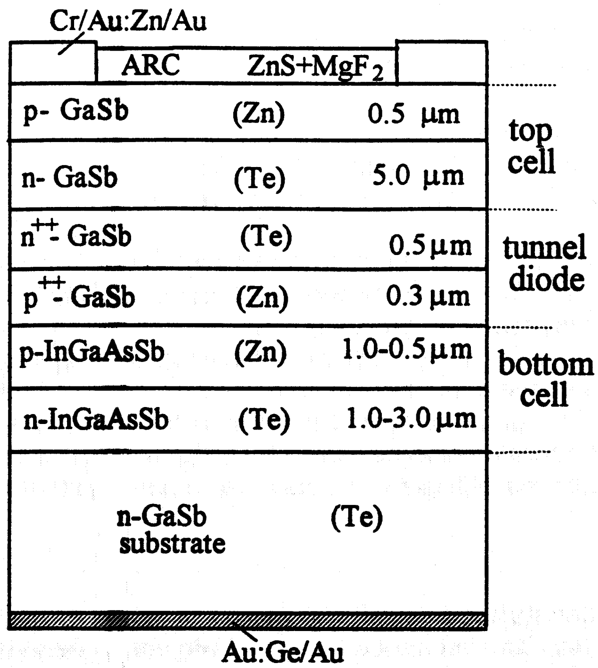

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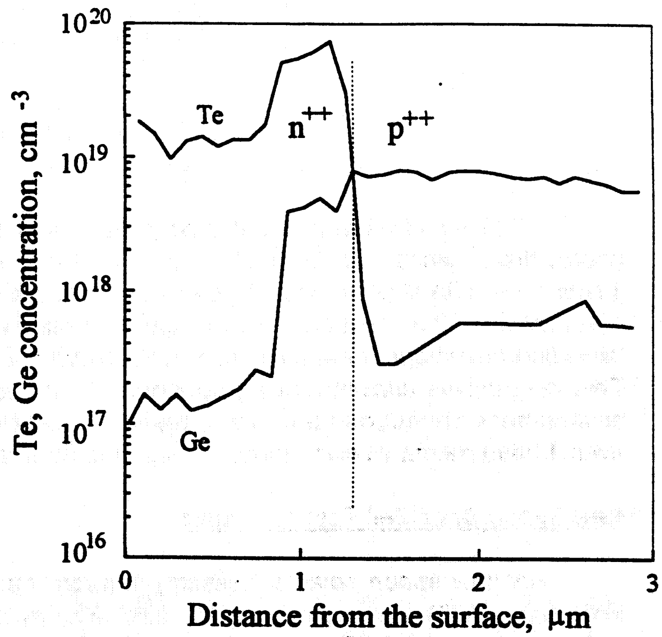

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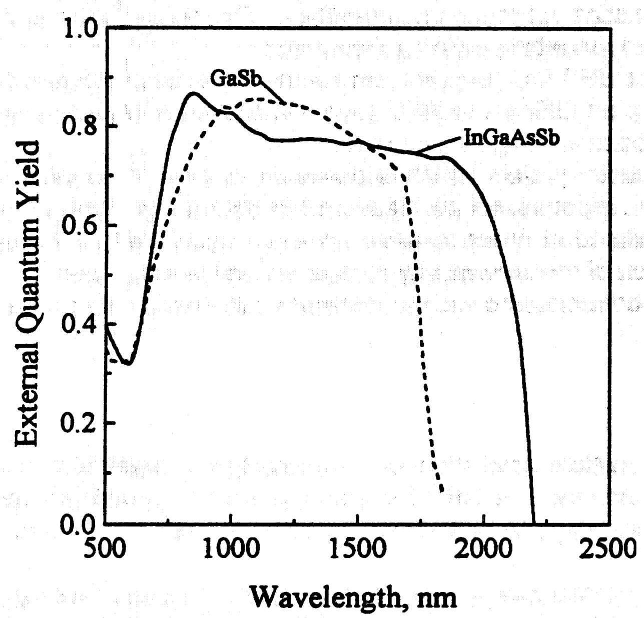

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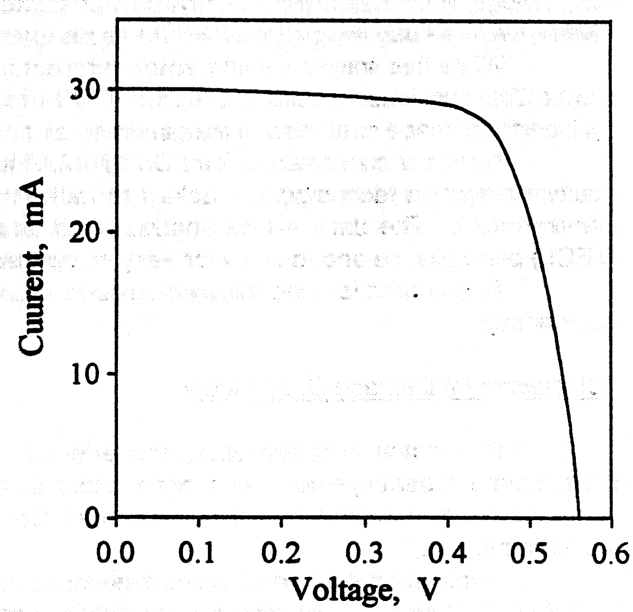

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