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A POSSIBLE RADIATION-RESISTANT SOLAR CELL GEOMETRY USING SUPERLATTICES

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A solar cell structure is proposed which uses a GaAs nipi doping superlattice. An important feature of this structure is that photogenerated minority carriers are very quickly collected in a time shorter than bulk lifetime in the fairly heavily doped n and p layers and these carriers are then transported parallel to the superlattice layers to selective ohmic contacts. Assuming that these already-separated carriers have very long recombination lifetimes, due to their being across an indirect bandgap in real space, it is argued that our proposed structure may exhibit superior radiation tolerance along with reasonably high beginning-of-life efficiency.

INTRODUCTION

In recent years, semiconductor superlattice (SL) structures have exhibited several attractive features. These include: 1) the ability to tailor-make a semiconductor with a desired bandgap and lattice constant over ranges of these two parameters which do not occur in normal materials (ref. 1), 2) the ability of a superlattice to act as a dislocation barrier which significantly reduces the propogation of dislocations from one semiconductor layer to another when an appropriate superlattice is interposed between them (ref. 2), 3) the exhibition of high electron mobility in undoped layers, in directions parallel to the layers, when such layers are alternated with heavily doped n-type layers of larger bandgap (ref. 3), and 4) the exhibition of very long carrier recombination lifetimes for excess carriers created in certain compositional and doping superlattice structures due to electrons and holes being confined in separate layers, thereby creating an effective "indirect bandgap in real space" (ref. 4).

A question naturally arises as to how one or more of these attractive features could be put to good use in solar cells. Blakeslee and Mitchell (refs. 2, 5), and Chaffin et al. (ref. 1) have proposed solar cell structures which utilize the first two features listed above in the monolithic multibandgap cascade solar cell geometry using binary and ternary III-V compounds. The principal advantage here is to be able to grow top and bottom cells of optimum bandgaps, $\sim$1.7eV and $\sim$1.1eV respectively, while minimizing lattice mismatch and/or the propagation of dislocations. Additionally, their structures make it possible to use the relatively inexpensive material silicon for the substrate and the bottom cell. It is not clear yet whether the requirement of carrier flow perpendicular to the superlattice layers in these

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structures, a direction generally regarded as having poor carrier transport properties, will pose a problem.

In this paper, we propose a superlattice solar cell structure in which carrier transport is parallel to the superlattice layers. It is a single-bandgap single-junction structure and therefore does not have the potential for the nearly 27 percent efficiency expected of the two-bandgap two-junction cascade device. However, by exploiting the very short carrier separation time and the very long carrier lifetime in a superlattice, our proposed GaAs-based structure is expected to yield a high radiation tolerance coupled with the 20% or so efficiency expected of a conventional GaAs solar cell designed for and operated under moderate sunlight concentration.

PROPOSED SUPERLATTICE SOLAR CELL STRUCTURE

Figure 1 shows our proposed GaAs-based superlattice solar cell structure. While quite different from them, it uses elements from two existing concentrator solar cell geometries, namely, the V-Grooved Multi-Junction (VGMJ) (ref. 6) and the Interdigitated Back Contact (IBC) (ref. 7) solar cells. Both of these structures have demonstrated high efficiencies in silicon.

The active region consists of a GaAs nipi doping superlattice of about 10 periods or 41 individual layers with a total thickness of 2.5 to 4 μm, grown on an appropriate semi-insulating substrate (all GaAs or GaAs on Ge-coated Si). The n^+ and p^+ regions in figure 1 are ion-implanted selective contacts to the n and p superlattice layers, respectively, and may be photolithographically fabricated using the same techniques as employed in the VGMJ solar cell (ref. 6). The n^+ and p^+ contacts are interdigitated as in the IBC cell (albeit in front instead of in the back), with all n^+ metallization stripes connected to one bus bar and all p^+ metallization stripes connected to another bus bar on the opposite edge.

OPERATION

Figures 2a and 2b show, under thermal equilibrium and under a forward bias respectively, the energy band diagram in a direction normal to the superlattice layers, say along the line aa in figure 1. If the dopings in the n and p layers and the thickness of the n, p and i layers are properly designed, then, in thermal equilibrium, the n and p layers will be completely covered by space charge, primarily due to ionized donors and acceptors respectively, so that E_c and E_v will be approximately parabolic functions of the space coordinate z. In the intervening i layers, E_c and E_v will be approximately linear functions of z. The total built-in band bending or diffusion potential depends on the dopings in the n and p layers and on the thicknesses of the n, p, and i layers.

The superlattice periodicity in the z direction, superimposed on the crystalline periodicity, causes the formation of electron and hole sub-bands within the conduction and valence bands respectively. The sub-band energies, widths, and densities-of-states depend on the exact manner in which E_c, E_v vary with z, and these, in turn, depend on the previous quantities, so that it turns out that all pertinent quantities, including $E_c(z)$, $E_v(z)$, the electron and hole concentrations n and p and their distribution in the sub-bands, must be solved self-consistently in thermal equilibrium and at any desired forward bias. Such calculations are

rather laborious and, to our knowledge, have been performed only for the case of the npnp superlattice without the i layers. Figures 3a, 3b and 3c show the results of such calculations as published by Brand and Abram (ref. 8). Such calculations are a first step toward the theoretical modelling and optimum design of the superlattice solar cell we are proposing. We have begun the project of doing such calculations for the nipi structure so that they will allow us to predict cell performance as a function of the widths of the n, p and i layers and the dopings in the n and p layers, and to optimize these parameters.

The i layers are needed to give the largest possible built-in band bending while still providing reasonably wide high-electric-field regions without requiring relatively thick heavily doped n and p regions. The large build-in band bending is needed in order to get a high open circuit voltage V_{oc}, and a wide high-electric field region is needed for a high carrier collection efficiency and high radiation tolerance.

Next, let us consider figure 2b, where the superlattice of figure 2a is shown under a forward bias, say that corresponding to the maximum power voltage under illumination. In this case, it is seen that part of the space charge in the n and p regions is compensated by mobile carriers, so that flat spots, corresponding to quasi-neutral regions, appear in E_c and E_v. In our solar cell structure, these quasi-neutral regions are not expected to be more than about 600 angstroms wide, so that a photogenerated electron in the middle of a p layer would diffuse to the nearest high electric field region in less than 3×10^{-11} seconds (using a diffusion velocity of $\geq 10^5$ cm/s for electrons in GaAs) and then drift at nearly the thermal velocity to the lowest available sub-band in the conduction band in another 10^{-12} second or less. Thus it is seen that an electron which is photogenerated anywhere in the structure is very quickly transported into the nearest n layer, where it is a majority carrier. By the same token, a hole which is photogenerated anywhere would also be transported into the nearest p layer in less than 3×10^{-10} second (using a diffusion velocity of $\geq 10^4$ cm/s for holes). Once they become majority carriers, these separated photogenerated carriers must still be transported, without recombination, to the nearest selective contacts before they can be regarded as being collected (that is, having contributed to external current).

In an ordinary solar cell, a photogenerated minority carrier would be regarded as having been collected once it had been separated, that is, once it crossed the junction space charge region and became a majority carrier. However, in a superlattice solar cell, in which relatively large numbers of electrons and holes are spatially confined in close proximity such that their wavefunctions overlap, band-to-band recombination of already-separated photogenerated electrons and holes can occur between a sub-band in the conduction band and a corresponding sub-band in the valence band. Such recombination is said to occur across an "indirect bandgap in real space". The larger the overlap between the electron and hole wavefunctions, the larger the rate of recombination. It is seen from figure 2b that electrons and holes in the lowest energy sub-bands do not have any significant overlap of their wavefunctions. Only the higher-energy sub-bands will have any significant overlap of wavefunctions. However, because of a rather large energy gap between these, the recombination probability is rather low. Thus, the overall recombination probability across an indirect bandgap in real space can be rather low, yielding an effective recombination lifetime that can be very long. In this regard, we have also taken a look at the use of Type I and Type II compositional superlattices in our proposed structure and have found that the nipi doping superlattice appears to offer the longest recombination lifetime of already-separated carriers across the indirect bandgap in real space.

We have performed some rather crude calculations for a GaAs nipi doping superlattice cell of dimensions shown in figure 4. This geometry is very similar to that of the GaAs concentrator cell designed for use with the venetian blind or slats type concentrator at moderate concentrations up to 20 AMO (ref. 9). The total illuminated cell area is 0.25 cm x 1 cm with 50 grid lines, 25 each for the n and p selective contacts and each approximately 10 μm wide and 0.25cm long. The n, p, and i layers are each 1000A thick, and there are 10 complete pini periods (11 p layers, 20 i layers and 10 n layers). With about 200 μm separation between adjacent selective n and p contacts, dopings of about 5×10^{18} cm^{-3} in the n and p layers, an illumination level of $\sim$ 5xAMO, and a short circuit current density of about 180 mA/cm^2, the time required by the already-separated electrons and holes to drift the farthest distance (equal to the grid separation of 200 μm) to the nearest selective contact is about 0.6 millisecond. Thus, the required recombination lifetime across the indirect bandgap in real space is about 1 millisecond or larger at the cell operating temperature (300-350K). Preliminary theory predicts such lifetimes to be possible. More detailed calculations and experimental verification have yet to be done.

DISCUSSION

The superlattice solar cell device structure we propose is expected to have a high short circuit current density J_{sc}, at least as high as with a well-designed conventional GaAs solar cell. This is because of the nearly complete collection of photogenerated carriers expected if the recombination lifetime for already-separated carriers is longer than 1ms. The slightly lower (than for bulk GaAs) effective bandgap (indirect in real space) is not expected to increase the number of photogenerated carriers and J_{sc} to any significant degree.

One may expect the open circuit voltage V_{oc} in this device to be lower than in the conventional GaAs solar cell for two reasons: 1) for a given illuminated area, the junction area is N times larger, where N is the number of nipi periods, 10 in our example, and 2) the forward or loss current pre-exponential factor J_o may be dominated by space charge recombination. It is not so much the larger junction area per se which is a problem. It is the larger overall volume of the space charge region compared to that in a conventional GaAs solar cell which may make the J_o of our superlattice cell relatively larger and give rise to a smaller V_{oc}. Even so, it is felt that a reasonably large V_{oc} may be obtainable at moderate sunlight concentrations.

It thus appears that the beginning-of-life (BOL) efficiency of our proposed cell might be somewhat smaller than that of a well-designed conventional GaAs solar cell, say, 20% instead of 22 to 23%. However, our proposed superlattice cell structure is expected to exhibit a high degree of radiation tolerance. This is because, at radiation exposures equivalent to a fluence of 10^{15} 1MeV electrons/cm^2 or less, the carrier collection efficiency is expected to stay very high, close to 100%, since for both electrons and holes, the minority carrier diffusion length after irradiation is expected to be longer than the 300-500A they have to diffuse in the quasi-neutral portions of the n and p layers before being separated. Additionally, since the recombination lifetime of already-separated carriers depends on the overlap in their wavefunctions, that lifetime is not expected to be affected by irradiation. Thus, the short circuit current density should suffer negligible degradation under irradiation. The open circuit voltage V_{oc} and fill factor FF are expected to degrade in our proposed cell because of increased J_o due to increased

recombination in the space charge region. It is not clear at this time whether the degradations in V_{oc} and FF can be kept low enough to yield an overall high radiation tolerance, but the present expectation is that with proper design they can. That is what we aim to find out through a detailed modelling and parameter optimization study of our proposed structure.

REFERENCES

1. Chaffin, R.J., et. al., "Strained Superlattice, Quantum Well, Multijunction Photovoltaic Cell", Conf. Rec. 17th IEEE PVSC, Orlando, Fla., May 1984, IEEE Publ. No. 84CH2019-8, pp. 743-746.

2. Blakeslee, A.E. and K.W. Mitchell, "Incorporation of Superlattice Crystal Layers in Multijunction Solar Cells", Conf. Rec. of Space Photovoltaic Research and Technology Conf., NASA Lewis, Cleveland, Oct. 1980, NASA Conf. Publ. No. 2169, pp. 131-134.

3. Dingle, R., H.L. Stormer, A.C. Gossard, and W. Wiegman, "Electron Mobilities in Modulation-doped Semiconductor Heterojunction Superlattices", Appl. Phys. Lett. Vol. 33, No. 7, 1 Oct. 1978, pp. 665-667.

4. Dohler, G.H., "Electrical and Optical Properties of Crystals with 'nipi-Superstructure'", Phys. Stat. Sol., Vol. 52, 1972, pp. 533-545.

5. Blakeslee, A.E., "Control of Superlattice Morphology in $GaAs_{1-x}P_x$ Cascade Cells", this proceedings.

6. Chappell, T.I., "The V-Groove Multijunction Solar Cell", Conf. Rec. 13th IEEE PVSC, Washington, D.C., June 1978, IEEE Publ. No. CH1319-3/78/0000-0791, pp. 791-796, also IEEE Trans. Electron Devices, ED-26, No. 7, 1979, pp. 1091-1097.

7. Schwartz, R.J. and M.D. Lammert, "Silicon Solar Cells for High Concentration Applications", Technical Digest, International Electron Devices Meeting (IEDM), Washington, D.C., Dec. 1975, p. 350, also IEEE Trans. Electron Devices, ED-24, No. 1977, p. 337.

8. Brand, S. and R.A. Abram, "Self-consistent Calculations of Electron and Hole Sub-band Energies for an n-p Superlattice in GaAs", J. Phys. C., Vol. 16, 1983, pp. 6111-6120.

9. Goradia, C.P., M. Ghalla-Goradia, and H. Curtis, "Near-optimum Design of GaAs-based Concentrator Space Solar Cells for 80°C Operation", Conf. Rec. 17th IEEE PVSC, Orlando, Fla., May 1984, IEEE Publ. No. 84CH2019-8, pp. 56-62.

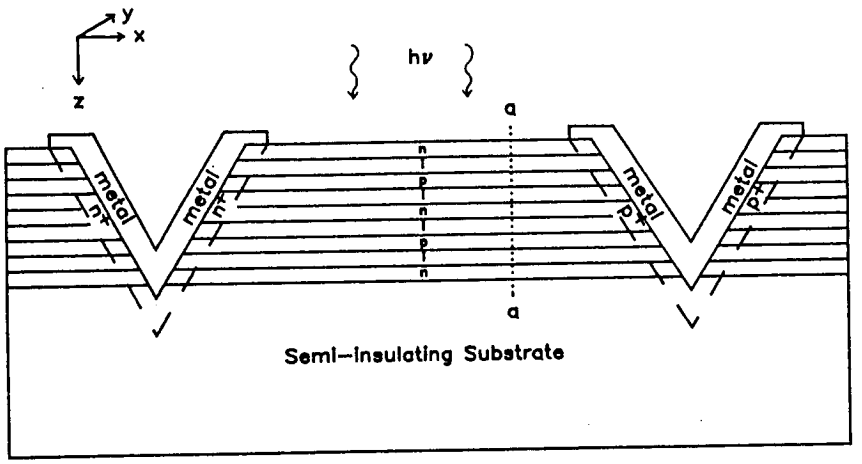


Figure 1: Schematic diagram of proposed solar cell structure using nipi doping superlattice.

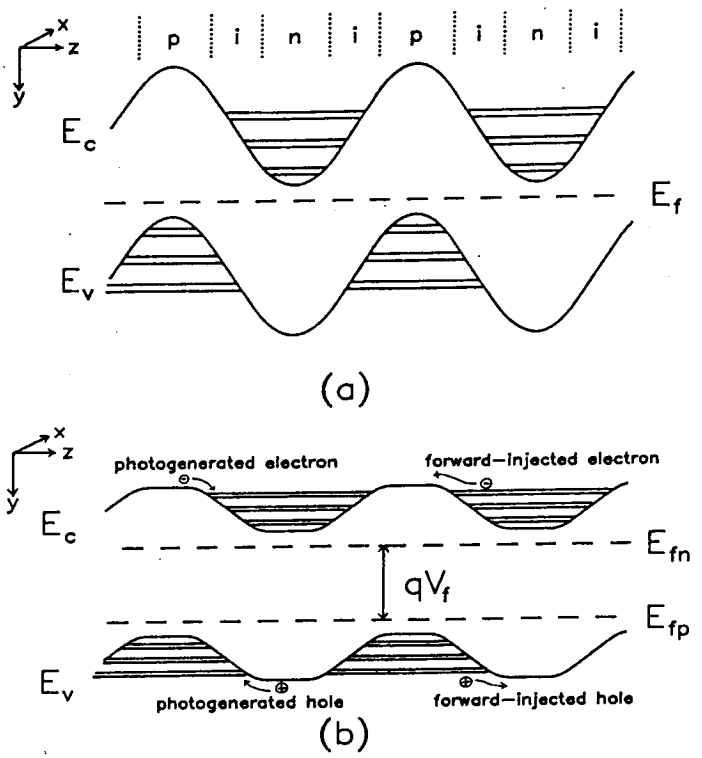
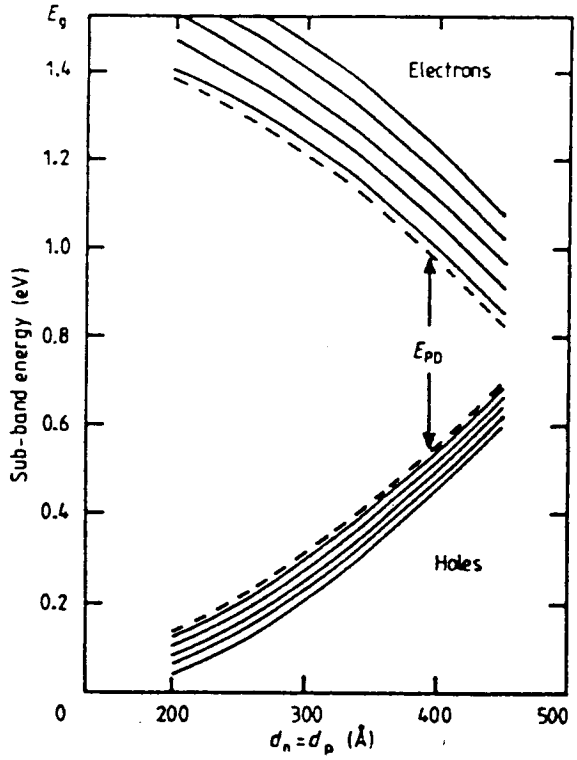
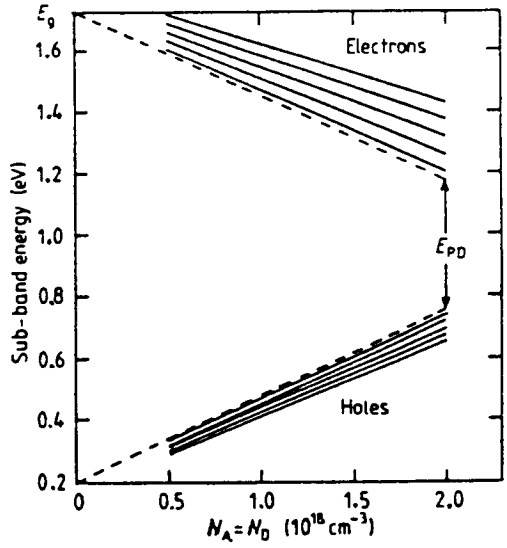


Figure 2: Band diagram of nipi superlattice, (a) in thermal equilibrium, and (b) under forward bias.



(a)



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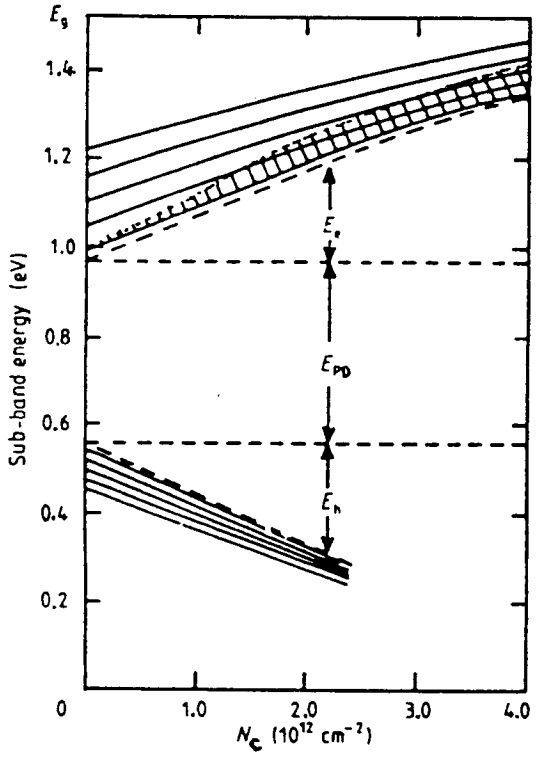

(c)

Figure 3: Electron and hole sub-band levels as a function of (a) layer thickness $d_n = d_p$, for $N_d = N_a = 2 \times 10^{18}$ cm^{-3}; (b) doping level $N_d = N_a$, for $d_n = d_p = 400$ Å; (c) 2-dimensional injected carrier concentration N_c, for $N_d = N_a = 2 \times 10^{18}$ cm^{-3} and $d_n = d_p = 400$ Å (the shaded area represents filled states). From reference 8.

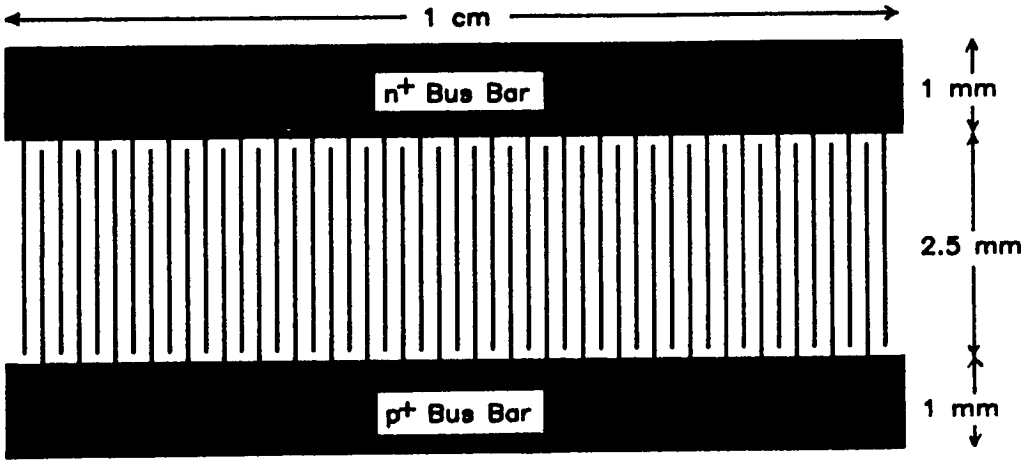

Figure 4: Top view of proposed superlattice cell, showing collection grid geometry and typical dimensions.