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DESIGN CONSIDERATIONS FOR A GaAs nipi DOPING SUPERLATTICE SOLAR CELL

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A new GaAs nipi doping superlattice solar cell structure is presented, which holds promise for a high efficiency coupled with very high radiation tolerance. This structure uses the CLEFT process and has all contacts on the unilluminated side. It is different from our structure proposed at the last SPRAT conference. Next, design constraints are presented which this structure must satisfy in order to exhibit high efficiency and high radiation tolerance. Finally, results of self-consistent quantum mechanical calculations are presented which show that a viable design of this cell would include relatively thick (~500 Å) n and p layers which are fairly heavily doped ($2x10^{18}$ to $5x10^{18}/cm^3$).

INTRODUCTION

At the previous SPRAT conference in 1985, we presented a GaAs nipi doping superlattice solar cell structure which showed promise for high efficiency and very high radiation tolerance (ref. 1). This structure is shown in figure 1. A unique feature of this structure was that photogenerated carriers are very quickly separated by the built-in electric field in times ranging from 10^{-12} sec to 10^{-10} sec and that these carriers then flow parallel to the superlattice layers, a direction of easy carrier flow. This is in contrast to strained-layer and other superlattice solar cell structures that have carrier flow normal to the layers, a direction of difficult carrier flow. However, it was also pointed out then that one major drawback of this structure was that, even after separation, the carriers could recombine across the "indirect gap in real space" before they reached their respective selective ohmic contacts. In addition, the photocurrent flows along the length of the thin layers between neighboring selective ohmic contacts and may lead to a severe series resistance problem. These two facts put constraints on the minimum lifetime of already-separated carriers across the indirect gap in real space, on the maximum distance between adjacent selective ohmic contacts, and on the minimum two-dimensional carrier densities in the n and p layers.

In order to calculate the lifetime across the indirect gap in real space, it is necessary to calculate the overlap integral of the electron and hole wavefunctions over one period of the superlattice, averaged over all the subbands of the conduction and valence bands. This requires self-consistent calculations between Schrödinger's equation and Poisson's equation, since the potential function in the

former equation is the solution to Poisson's equation and the charge density function in the latter depends on the solution to Schrodinger's equation. These calculations are rather difficult and time-consuming, and we had just begun them at the time of the previous SPRAT conference.

CELL STRUCTURE

We have now completed these self-consistent quantum mechanical calculations for a large number of combinations of layer thicknesses of the n, i, and p layers and of dopings in the n and p layers. These results have shown that our original structure of figure 1 would not work efficiently. We have come up with the modified structure of figure 2 which is based on the CLEFT process (ref. 2) and has all contacts on the back side, making it possible to have closely spaced contacts without having to worry about grid shadowing.

Figure 2(a) gives a basic idea of the method of cell fabrication. Starting with a GaAs substrate, a thin epitaxial layer of GaAs is grown as in the CLEFT process (ref. 2). On this is grown an undoped AlGaAs layer of appropriate thickness (0.2 to 0.5 μm); this layer will serve as a window for the finished cell. On the AlGaAs layer is grown the GaAs nipi superlattice with 10 periods of 0.1- to 0.2 μm each for a total thickness of 1 to 2 μm. V-grooves are photolithographically etched in the superlattice (ref. 3), and alternate grooves are ion-implanted n^+ and p^+ in an interdigitated fashion. The grooves are then metallized to form ohmic contacts to the n^+ and p^+ selective contacts. A rigid backing is then applied for structural support, leaving only the n^+ and p^+ bus bars exposed for external contacts. The backing material should be a good thermal conductor but an electrical insulator. The cell is then cleaved off the GaAs substrate by the CLEFT process (ref. 2), and the GaAs layer above the AlGaAs window is etched off. Finally, an antireflection coating is applied over the AlGaAs window. The finished cell is shown in figure 2(b), with light entering through the AlGaAs window.

DESIGN CONSTRAINTS

We have taken a close look at the design constraints that must be satisfied in order for the cell to exhibit high efficiency and high radiation tolerance. We have derived expressions for the minimum lifetime across the indirect gap in real space, and the minimum values of carrier concentrations in the n and p layers required to keep series resistance and recombination losses within acceptable levels. All of the design constraints are treated in detail in reference 4. Here, we summarize these constraints for the GaAs nipi superlattice solar cell of figure 2(b), operating at 20 AMO, 27 °C (300 K). They are as follows:

(1) total superlattice height or thickness of at least 1- to 2-μm to absorb most of the incident photons;

(2) at least 8 to 10 superlattice periods in order for our quantum mechanical calculations to apply;

(3) a distance between neighboring selective ohmic contacts of about 20 μm;

(4) highly reflecting rear metallization;

(5) thicknesses of n, i, p layers and dopings in n and p layers such that under operating conditions at a forward voltage of about 1.00 V (estimated to be the maximum power voltage at 20 AMO, 300 K) the average electron and hole concentrations are at least $5 \times 10^{17}/cm^3$ and the lifetime for recombination across the indirect gap in real space is at least 10 μsec;

(6) thicknesses of the n and p layers no larger than about 600 Å, so that even after irradiation to a fluence of 1×10^{16} 1 MeV electrons/cm^2 or 1×10^{13} 10 MeV protons/cm^2, the maximum distance a carrier has to diffuse in a low-electric field region is shorter than the carrier diffusion length.

RESULTS

Table I shows the various combinations of layer thicknesses and dopings considered. The lifetimes of already-separated carriers are plotted versus the forward voltage in figure 3. For an open circuit voltage of 1.1 V and an operating voltage (at maximum power) of about 1.0 V, it is seen that most combinations give lifetimes of about 10 msec or larger. Figure 4 shows the average hole concentration in the p layers versus the forward voltage. For the CLEFT type structure of figure 2(b), operating at 20 AMO and 27 °C, we have calculated that for a 20-μm spacing between adjacent contacts, the required minimum lifetime of already-separated carriers is ~10 μsec and the required average hole concentration is $5 \times 10^{17}/cm^3$, in order to keep the ohmic voltage drop across the series resistance to about 20 mV at short circuit. From figure 4, combinations 1, 2, and 15 from table I appear promising, 15 being perhaps the most promising. It then appears that, in order to meet the design constraints outlined earlier, the most convenient design of this cell would have the n and p layers of thickness around 500 Å, with relatively heavy dopings of 2×10^{18} to $5 \times 10^{18}/cm^3$, and i layers may be thin or thick (~500 Å). The lifetime requirement is easily met by just about any combination of thicknesses and dopings; the constraint on minimum carrier concentrations to minimize the series resistance loss is the more stringent requirement.

We have not yet theoretically generated the illuminated I-V characteristics of this device so as to give us the calculated performance parameters, both at beginning of life and after irradiation. Hence, at the present time, we cannot provide any calculated numbers on the expected efficiency and radiation tolerance of this device. This is an extremely difficult and laborious problem requiring 2 to 3 more years of work. However, it is possible to argue on theoretical grounds, as we have done previously (refs. 1 and 4), that this structure should exhibit a beginning-of-life efficiency that is nearly the same but somewhat smaller than that of a well-designed conventional GaAs concentrator solar cell operating under the same conditions and should exhibit a very high radiation tolerance. The next step is the actual fabrication and testing of this structure.

REFERENCES

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2. McClelland, R.W.; Bozler, C.O.; and Fan, J.C.C.: A Technique for Producing Epitaxial Films on Reusable Substrates. Appl. Phys. Lett., vol. 37, no. 6 Sept. 15, 1980, pp. 560-562.

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TABLE I. - COMBINATIONS OF LAYER THICKNESSES AND DOPINGS CONSIDERED FOR SELF-CONSISTENT CALCULATIONS AND USED IN PLOTTING FIGURES 3 AND 4

Superlattice	d(A)	d_n	d_p	d_i	N_d	N_a
1	800	175	175	225	5×10^{18}	5×10^{18}
2	1000	469	469	31	2×10^{18}	2×10^{18}
3	1200	338	338	262	1.5×10^{18}	1.5×10^{18}
4	1200	562	562	38	1×10^{18}	1×10^{18}
5	1400	656	656	44	1.1×10^{18}	1.1×10^{18}
6	1400	656	656	44	8×10^{17}	8×10^{17}
7	1400	394	394	306	1×10^{18}	1×10^{18}
8[a]	1400	394	394	306	1×10^{18}	1×10^{18}
9	1400	394	394	306	2×10^{18}	2×10^{18}
10	1400	219	219	481	2×10^{18}	2×10^{18}
11	1400	394	1006	0	2×10^{18}	6.7×10^{17}
12	1600	450	450	350	8×10^{17}	8×10^{17}
13	1300	750	750	50	1×10^{18}	1×10^{18}
14	2000	562	562	438	5×10^{17}	5×10^{17}
15	2000	562	562	438	5×10^{18}	5×10^{18}
16	4000	1875	1875	125	1.6×10^{17}	1.6×10^{17}

[a]Superlattice 8 used $m_e^* = m_h^* = 0.067m_e$.

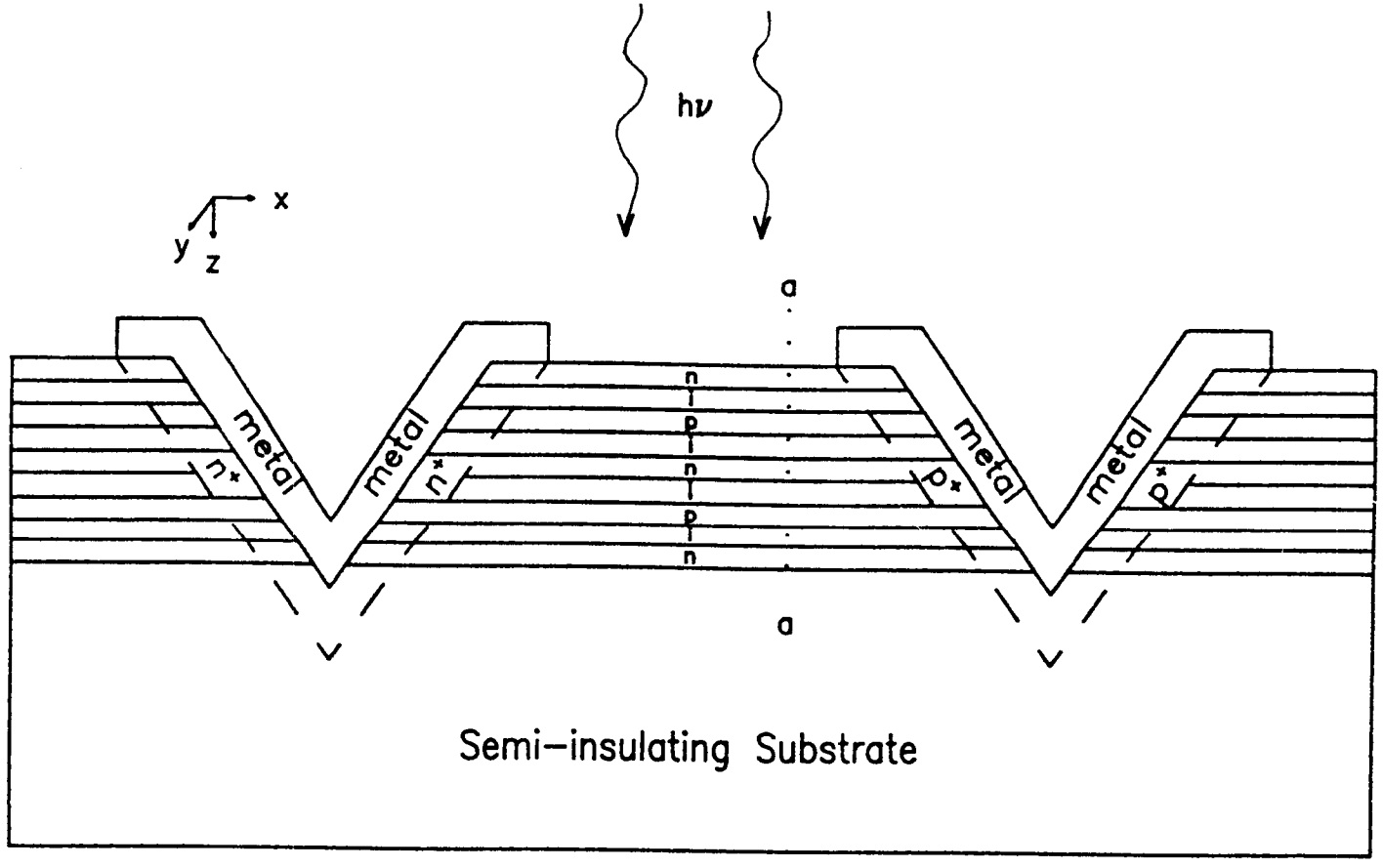
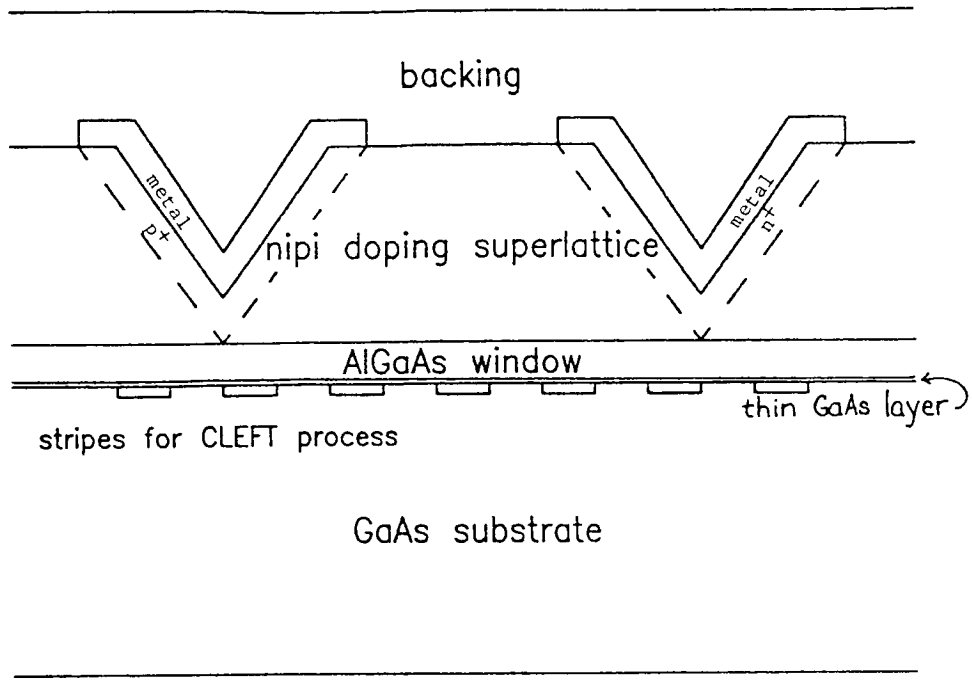
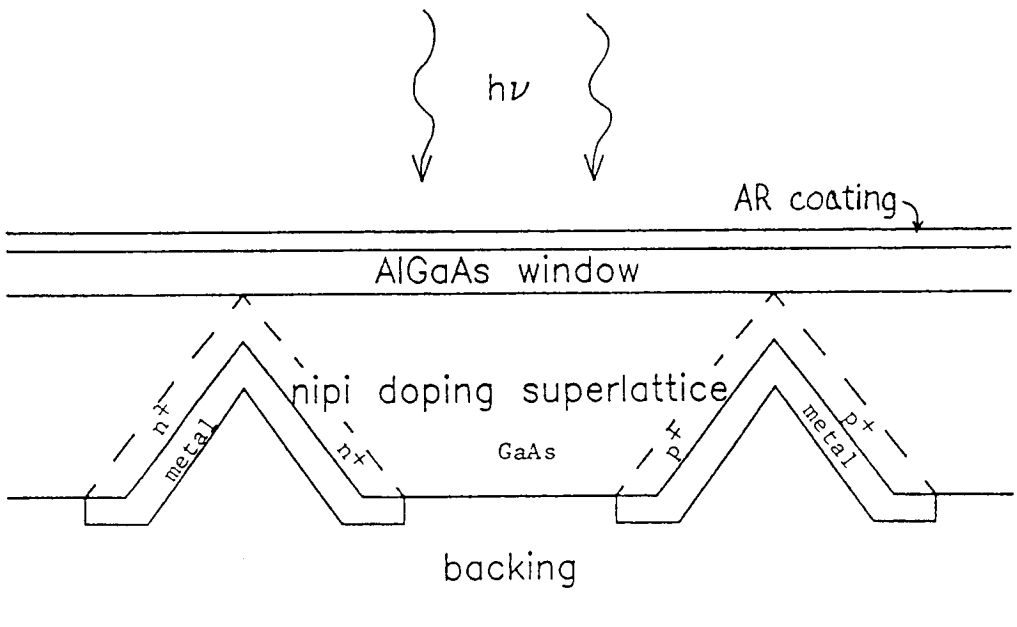


Figure 1. - Doping superlattice solar cell structure as originally proposed.



(a) Schematic of fabrication procedure.



(b) CLEFT superlattice solar cell in use.

Figure 2. - Improved solar cell structure using CLEFT process.

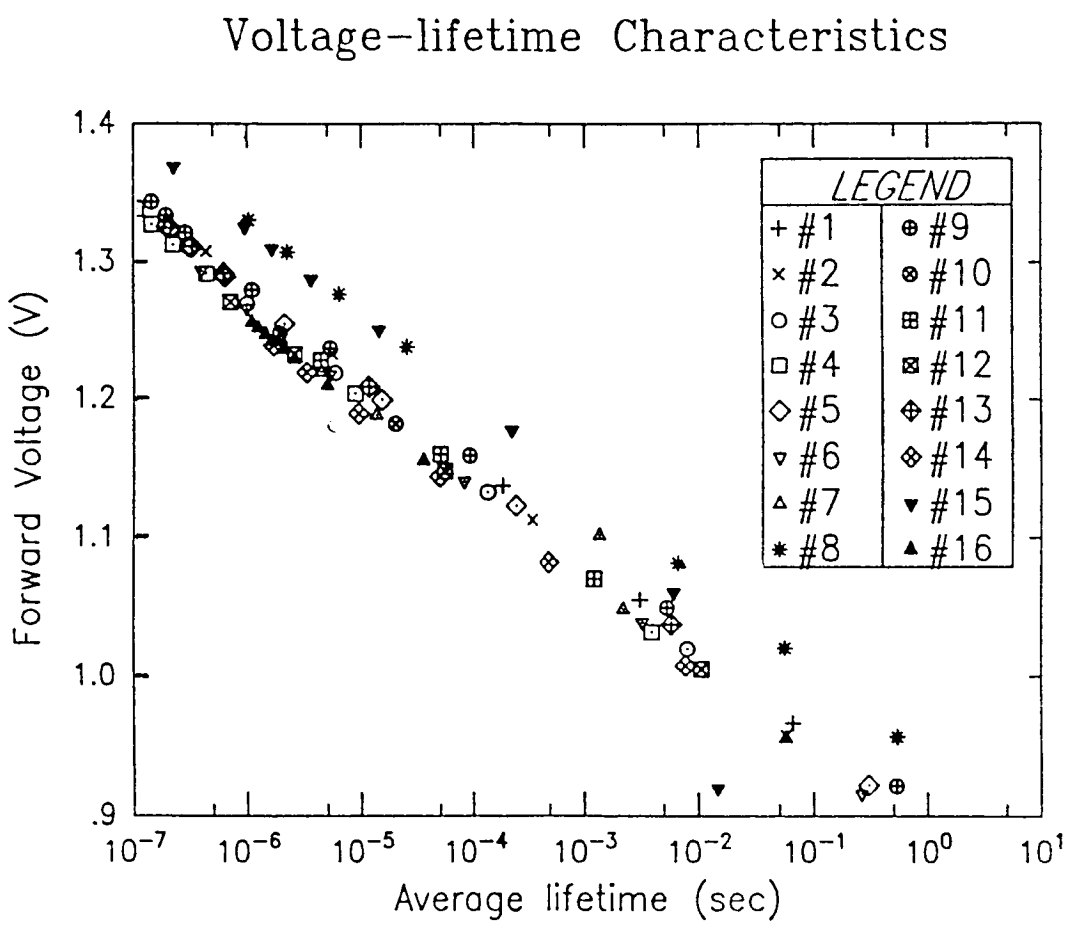


Figure 3. - Lifetime versus forward voltage characteristics for the superlattices in table I.

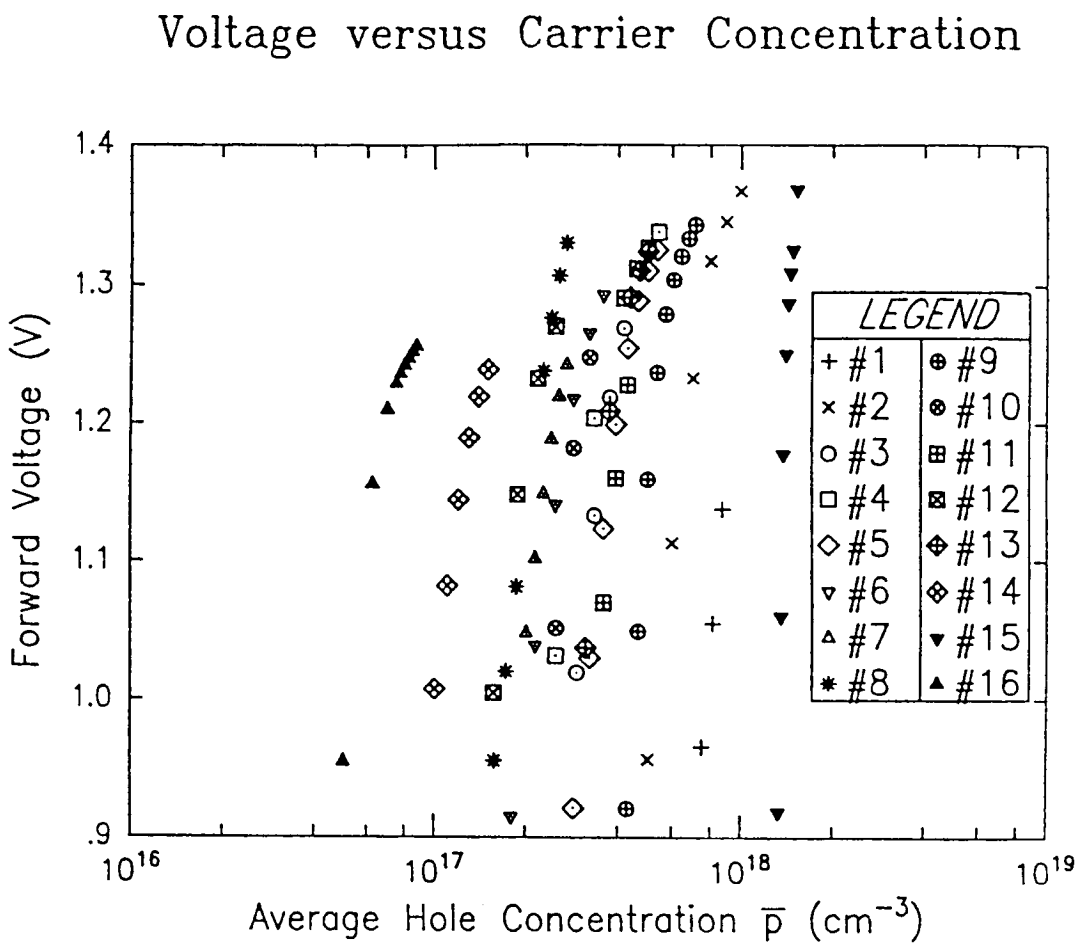


Figure 4. - Carrier concentration versus forward voltage for the superlattices in table I.