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Lateral Superlattice Solar Cells

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A novel structure which comprises of a lateral superlattice as the active layer of a solar cell is proposed. If the alternating regions A and B of a lateral superlattice ABABAB... are chosen to have a Type-II band offset, it is shown that the performance of the active absorbing region of the solar cell is optimized. In essence, the Type-II lateral superlattice region can satisfy the material requirements for an ideal solar cells active absorbing region, i.e. simultaneously having a very high transition probability for photogeneration and a very long minority carrier recombination lifetime.

INTRODUCTION

In the design of solar cells one seeks to optimize performance based on choice of materials and device architecture. Invariably, the constraints for this optimization are inherently associated with availability of materials, ease of manufacture, reliability, application (terrestrial or space), and cost which in turn depends on several of the prior criteria. For terrestial flat plate applications, large area polycrystalline or amorphous thin film or polysilicon solar cells satisfy the large active area and low cost requirements, whereas for space and concentrator applications epitaxially grown alloys and tandem solar cell designs are more suitable. Whatever be the solar cell design philosophy employed, it will be based on certain design trade-offs. It is not the purpose of this paper to deal with the above mentioned issues, but to address at a much more fundamental level the constraints imposed by the trade-off between two very important solar cell material performance parameters, namely the minority carrier lifetime and the transition probability for photogeneration in conventional solar cell designs, and to examine if it is possible to overcome present day limitations.

BACKGROUND

The photo-generation of minority carriers that results from the absorption of sunlight in the active region of a solar cell must be very efficient for optimal cell performance and so the material chosen for this region should have a strong absorption coefficient. Direct bandgap semiconductors such as GaAs have strong absorption coefficients because the efficiency with which above bandgap photons are converted into photogenerated carriers is large. Indirect bangap materials such

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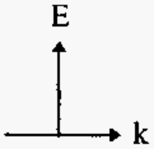
as Si have weak absorption coefficients (typically three orders of magnitude lower than that of GaAs) because here the efficiency with which above bandgap photons are converted into photogenerated carriers is low. As shown in Fig. 1b, the incoming photon is only able to photo-generate carriers with the assistance of a momentum conserving phonon which lowers the probability for such processes considerably in comparison to those in Fig. 1a.



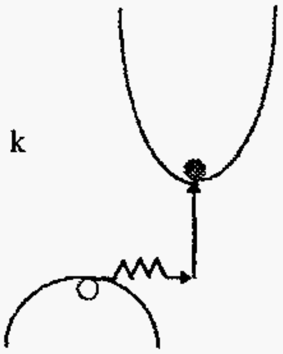
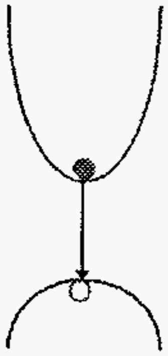
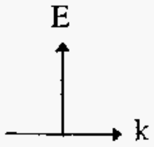


Figure 1a. Direct gap absorption

Figure 1b. Indirect gap absorption

In a solar cell, the photogenerated minority carriers must live long enough to be collected and so minority carrier lifetimes in the material comprising the active region should be large. As shown in Fig. 2a, in direct bandgap semiconductor alloys such as GaAs the radiative recombination of photogenerated carriers does not require the assistance of a phonon and so occurs relatively easily resulting in short recombination lifetimes (on the order of microseconds). On the other hand, this process can only occur with the assistance of a momentum conserving phonon in indirect bandgap semiconductors such as Si, making it much less probable, and thus resulting in long lifetimes (on the order of milliseconds). There thus appears to be a fundamental constraint in obtaining a material with both a high transition probability for photogeneration as well as a long recombination lifetime, in the sense that if one optimizes one of these parameters one has to trade-off on the other. This is an intrinsic limitation which is inherent in the choice of semiconductor alloys used for conventional solar cells. In the following section we examine if it is possible to overcome this limitation.





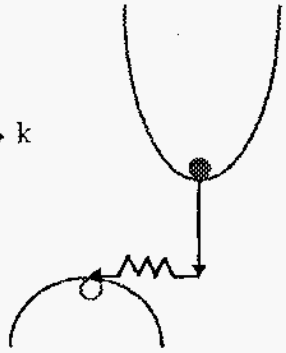


Figure 2a. Direct gap recombination

Figure 2b. Indirect gap recombination

LATERAL SUPERLATTICE SOLAR CELLS

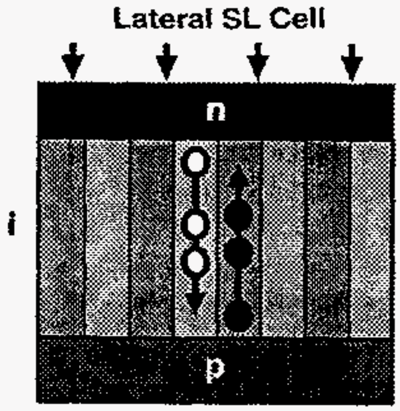


Figure 3a. Schematic of the solar cell.

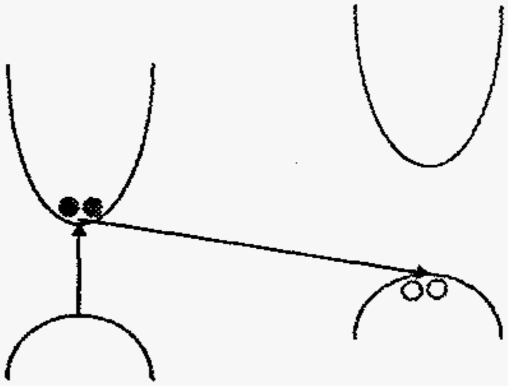


Figure 3b. Spatial band alignment.

Consider the solar cell shown in Fig. 3a in which the active region comprises of a lateral superlattice ABABAB.. for which the band offset between the alternating regions A and B is type-II and is shown schematically in Fig. 3b. Sunlight is efficiently converted into photogenerated carriers in regions A and B since each has a direct bandgap. If the periodicity of the lateral superlattice is of the order of a few hundred Angstroms, then the photogenerated electrons quickly diffuse to the lowest conduction band regions of the superlattice whereas the holes quickly diffuse to the highest valence band regions of the superlattice.

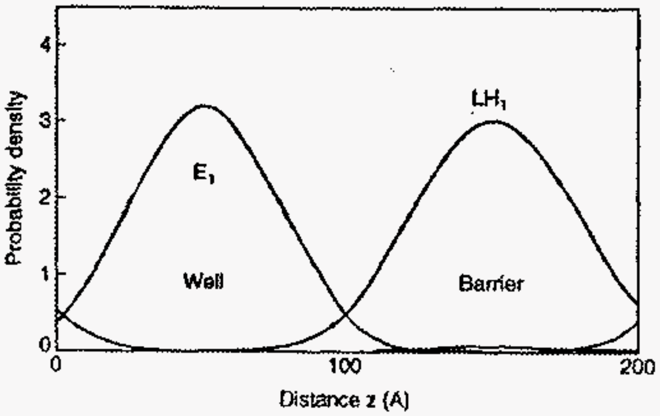


Figure 4. Spatial probability distribution of electrons and holes in a Type-II superlattice.

For the case of a lateral superlattice generated by spontaneous compositional modulation during growth of a GaP/InP short period vertical superlattice structure, a plot of the resulting spatial probability distribution(1) for photogenerated electrons and holes is shown in Fig. 4. Here a valence band offset (in the abscence of strain) of merely 10 meV was assumed to study the effect this has on the spatial localization of carriers. As is evident in Fig. 4, the spatial overlap between the wavefunctions for electrons and holes is very small and so even though the superlattice is direct in k-space it is indirect in real space. The only way for the spatially separated photogenerated electrons and holes to recombine radiatively is by lateral tunneling through their respective barriers thereby making the electron and hole wavefunction overlap integral non-zero. Since the probability for such lateral tunneling is very small in the absence of a lateral electric field, the recombination between the photogenerated electrons and holes is drastically reduce in such a superlattice structure. Such structures (see Fig. 5) thus overcome the intrinsic semiconductor material limitations discussed in the previous section and make it possible simultaneously achieve both a high transition probability for photogeneration as well as a very long photo carrier recombination lifetime.

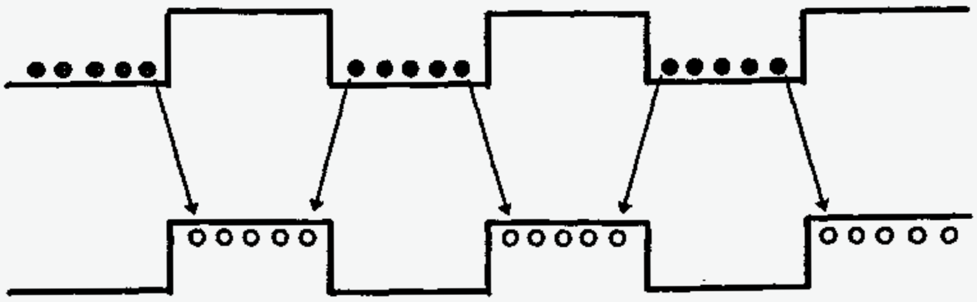


Figure 5. Spatial separation of electrons and holes in a Type II lateral superlattice.

The reason why this cannot be achieved in a conventional vertical superlattice can be seen from Fig. 6. In such a structure, even if the alternating regions of the superlattice are constructed from direct band gap semiconductors with a Type-II band alignment, the photogenerated electrons and holes are not constrained to move in spatially separated regions as they are swept towards the n and p regions of the solar cell respectively. The electron and hole paths and hence their wavefunctions have a strong spatial overlap in such a structure, and so there is no improvement as regards enhancement of photo carrier recombination lifetime.

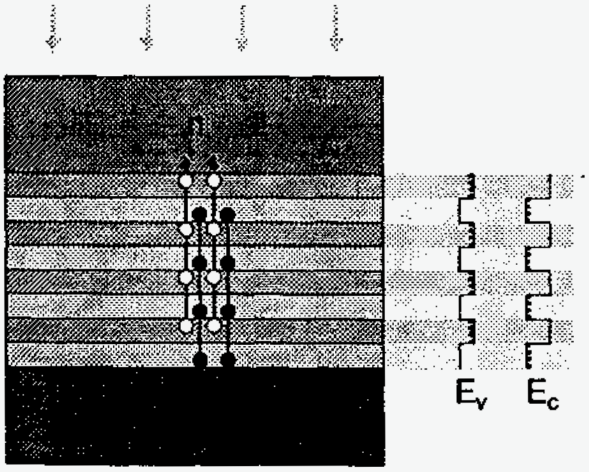


Figure 6. Schematic of a Type-II vertical superlattice solar cell

SYNTHESIS OF LATERAL SUPERLATTICE STRUCTURES

Although the synthesis of vertical superlattice structures using Molecular beam Epitaxy (MBE) and Organo-metallic Vapor Phase Epitaxy (OMVPE) techniques has been well established, the synthesis of lateral superlattice structures is relatively new and far more difficult. Techniques such as growth on V-groove patterned substrates(2) or use of metallic stripe overlayers for strain pattern transfer(3)have been employed to fabricate lateral quantum wires but they both involve elaborate and costly processing steps and are incapable of yielding small lateral periodicity's. Recently there have been several(4,5) experimental demonstrations of a relatively simple method for generating lateral superlattice structures which does not require any elaborate processing steps and is compatible with MBE and OMVPE techniques. The method relies on the phenomenon of spontaneous composition modulation in ternary semiconductor alloys ABC_2 or in vertical short period superlattice (SPS) structures $(AB)_n/(AC)_n$, where the binary constituents AB and AC are size mismatched.

Cross Sectional TEM

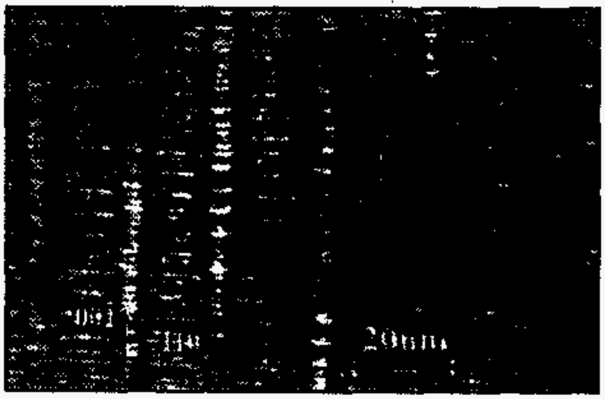


Figure 7. X-TEM image showing lateral composition modulation

As shown in Fig. 7, Mirecki et al. have demonstrated the spontaenous formation of lateral superlattices with periodicities of around 130 Å during growth of SPS structures of InAs/AlAs using MBE(5). Another group(4) has demonstrated the spontaneous formation of lateral superlattices during OMVPE growth of AlInAs epilayers on InP substrates. A similar phenomenon has been earlier demonstrated in the InP/GaP system and the InAs/GaAs system(6,7). It should be noted that in all these lateral superlattices the periodicity is not very regular but the structural quality is high as evidenced by the absence of dislocations. Although the type of band offset between the compositionally modulated regions in any of these structures has not yet been established it appears that this technique of achieving lateral superlattices could be useful for designing ideal solar cell structures in situations where the band offset between the compositionally modulated regions is Type-II. The lack of perfect regularity in the lateral periodicity exhibited in these structures is not of serious consequence for the application regarding solar cells since the only purpose of the lateral composition modulation here is to isolate the photogenerated electrons from the photogenerated holes.

CONCLUSION

It is shown that the performance of the active absorbing region of the solar cell is optimized if it is synthesized using a lateral superlattice ABABAB.... in which regions A and B comprise semiconductor alloys with direct bandgaps that are optimized to the solar spectrum and have a type-II band allignment with respect to each other. It is shown that the Type-II lateral superlattice can satisfy the material requirements for an ideal solar cells active absorbing region, i.e. simultaneously having a very high transition probability for photogeneration and a very long minority carrier recombination lifetime. The spontaneous lateral composition modulation technique offers the possibility of practically realizing such structures for solar cell applications.

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REFERENCES

1. A. Mascarenhas, R.G. Alonso, G.S. Horner, and S. Froyen, *Phys. Rev. B*48, 4907-4909 (1993).
2. G. Biasiol, F. Reinhardt, A. Gustafsson, E. Martinet, and E. Kapon, *Appl. Phys. Lett.* **69**, 2710-2712 (1996).
3. K. Kash, J. M. Worlock, M. D. Sturge, P. Grabbe, J. P. Harbison, A. Scherer and P. S. D. Lin, *Appl. Phys. Lett.* **53**, 782-784 (1988).
4. Sung Won Jun, Tae-Yeon Seong, J. H. Lee and Bun Lee, *Appl. Phys. Lett.* **68**, 3443-3445 (1996).
5. J. Mirecki Millunchick, R. D. Twesten, D. M. Follstaedt, S. R. Lee, E. D. Jones, Yong Zhang, S. P. Ahrenkiel, and A. Mascarenhas, *Apl. Phys. Lett.* **70**, 1402(1997).
6. K.C. Hsieh, J.N. Baillargeon, and K.Y. Cheng, *Appl. Phys. Lett.* **57**, 2244-2246 (1990).
7. K.Y. Cheng, K.C. Hsieh, and J.N. Baillargeon, *Appl. Phys. Lett.* **60**, 2892-2894 (1992).

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