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Application of photoluminescence and electroluminescence techniques to the characterization of intermediate band solar cells

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Abstract

The intermediate band solar cell (IBSC) is a photovoltaic device with a theoretical conversion efficiency limit of 63.2%. In recent years many attempts have been made to fabricate an intermediate band material which behaves as the theory states. One characteristic feature of an IBSC is its luminescence spectrum. In this work the temperature dependence of the photoluminescence (PL) and electroluminescence (EL) spectra of InAs/GaAs QD-IBSCs together with their reference cell have been studied. It is shown that EL measurements provide more reliable information about the behaviour of the IB material inside the IBSC structure than PL measurements. At low temperatures, the EL spectra are consistent with the quasi-Fermi level splits described by the IBSC model, whereas at room temperature they are not. This result is in agreement with previously reported analysis of the quantum efficiency of the solar cells.

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Intermediate band solar cell, solar cell characterization, photoluminescence, electroluminescence

1. Introduction

The intermediate band solar cell (IBSC) [1] is a novel concept for a photovoltaic device capable of

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surpassing the Shockley and Queisser efficiency limit [2] of single gap solar cells (SGSCs). The key to the high efficiency of this device lies on the presence of an electronic intermediate band (IB) within the semiconductor fundamental gap, E_G [see Figure 1 (a)]. The existence of the IB introduces two sub-band gaps (SBGs): one between the conduction band (CB) and the IB, E_L, and another one between IB and the valence band (VB), E_H. Thus, electrons have an alternative way to be promoted from the VB to the CB via the transitions labelled 1 and 2 in Figure 1 (a). In the IBSC each band has one quasi-Fermi level (QFL) ε_F associated to it. The split between each pair of QFLs means that the relaxation time between two bands is much larger than the relaxation time within a band. Therefore, three recombination rates can be defined (labelled 1', 2' and 3' in the figure), which in the ideal case are radiative. The photon flux emitted in the radiative recombination between a pair of bands depends on the split between of the QFLs associated to those bands through the generalized Planck Equation [3]. Figure 1 (b) illustrates the luminescence spectrum expected from an IBSC, in which three emission peaks, at energies E_G, E_H and E_L are present.

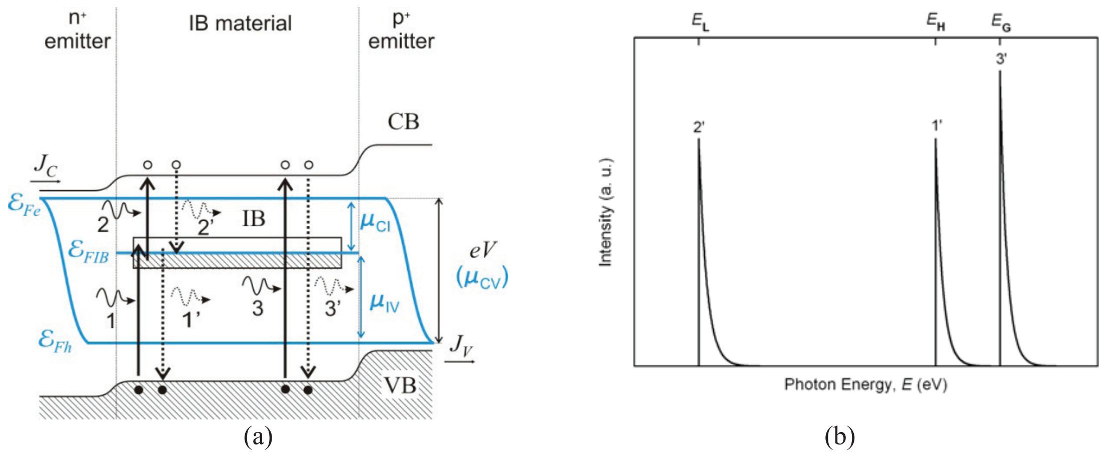

Figure 1: (a) Simplified band diagram of an IBSC under illumination and positive bias. ε_{Fe}, ε_{Fh} and ε_{FIB} are the QFLs associated with the CB, VB and IB, respectively. μ_{CI}, μ_{CV}, μ_{IV} represent the three QFL splits. (b) Example of photo- or electroluminescence spectrum expected from an IBSC.

Many efforts have been made to fabricate an IB material and an IBSC which behaves as theory dictates [4-7]. To date, most attempts to fabricate an IB have consisted of embedding InAs quantum dots (QDs) in GaAs [8]. The confined states introduced by the QDs provide the desired IB. The IBSC theory states that the output voltage of the cell is limited solely by the fundamental band gap, E_G, and not by the SBGs introduced by the IB. However, the devices until now fabricated presented a voltage drop with respect to their reference cell (a cell with the same structure of the IBSC but without the IB material) [4-7]. Some voltage drop is unavoidable in the IBSC if there is no QFL split between the CB and the IB (i.e. the relaxation of electrons between the CB and the IB is too fast). It has been reported that this is the case for state-of-the-art InAs/GaAs QD-IBSC prototypes at room temperature [9]. It has been proposed [10] that photoluminescence (PL) and electroluminescence (EL) measurements are two suitable techniques for the characterization of IB materials and IBSCs. In this work temperature dependent PL and EL measurements have been carried out for two InAs/GaAs QD-IBSCs to examine the extent to which these techniques are valuable for the evaluation of the behavior of IBSCs manufactured with current technology.

2. Experimental

One GaAs reference sample, labeled SR, and two InAs/GaAs QD-IBSCs samples, labeled SB and SC, manufactured at the University of Glasgow, have been measured. They have been produced by solid-source molecular beam epitaxy (MBE). SB and SC contain a stack of InAs QD layers, grown in the self assembled Stranski-Krastanov mode with Si-δ-doping, and sandwiched between a Si-doped n-GaAs emitter (0.2 µm for SB and 3.1 µm for SC) and an overlying 0.9 µm Be-doped p-GaAs emitter. Sample SB contains 30 layers of QDs separated by 84 nm spacers. Sample SC has 10 layers of QDs separated by 13 nm spacers. Further information on the structure and growth of these samples can be found in [9]. Sample SR has a similar structure than SC with the exception of the QD stack. Samples were mounted in a He closed-cycle cryostat providing a temperature range from 7 K to 300 K. In the PL measurements a 632.8 nm He-Ne laser was used to excite the samples. The approximated light power density on the samples was 0.5 W/cm^2. In the EL measurements a square pulse generated by a current source was used to excite the samples. The amplitude of the pulse was 0.90 A/cm^2 for SR, 0.75 A/cm^2 for SB and 0.60 A/cm^2 for SC. Luminescence from the samples was collected and guided trough a 1/8 m monochromator. Calibrated Si and Ge detectors were employed for light detection.

3. Results and discussion

Figure 2 shows the PL and EL spectra of samples SR, SB and SC. As expected for SR, a single luminescence peak can be seen in both types of spectra (at around 1.4 eV at room temperature). We identify this peak with the gap E_G of the GaAs. The intensity of this peak increases with decreasing temperature. One explanation for this is that non radiative recombination mechanisms, such as Shockley-Read-Hall recombination, are much less efficient at low temperatures, while radiative mechanisms have weaker temperature dependence and will then prevail at these lower temperatures.

In the PL spectra of samples SB and SC, the peak labelled A, associated with E_G, is observed at all temperatures. Peak B is identified as the emission involving the ground states of electrons of the QDs, i.e. it is related to E_H . This peak is strongly reduced at low temperatures. Peak C (and peak D for SC) are related to the recombination from the QDs excited states to the VB [11]. It could be interpreted that these results are in agreement with IBSC theory at all temperatures, as two peaks at energies E_G and E_H are always present, which would mean that three 'large' QFL splits are attained (E_L, which should also be present, is beyond our detection limit). However, this interpretation is not supported by the EL spectra.

Contrarily, in the EL spectra of SB and SC the peak A only appears at low temperatures, whereas the emission of the QDs follows a tendency similar to that of the PL spectra. These results show an IBSC-like behavior present only at temperatures below 125 K and not at higher temperatures, at which peak A is not present. This can be explained by the fact that the carrier relaxation from the CB to the IB is too fast at room temperature and there is no QFL split between those two bands. Then, the luminescence resulting from recombination form the IB to the VB is dominant over that resulting from recombination form the CB to the VB. This interpretation is in agreement with previous studies carried out on these cells. In [9] the thermal escape of electrons from the IB to the CB is demonstrated. Likewise, a fast thermal (non-radiative) relaxation exists in these samples, making the recombination path CB→IB→VB dominant over the direct CB→VB path. The thermal escape is strongly reduced, and finally suppressed, by lowering the temperature of the sample. Similarly, the thermal relaxation between CB and IB is less efficient with decreasing temperature, favoring the separation of ε_{Fe} and ε_{FIB} (two distinct electronic populations can be statistically described), and both recombination paths compete.

A possible explanation for the difference in the PL and EL results is that the measured PL spectrum includes the luminescence from the emitters in addition to that from the IB material. Due to the finite carrier mobility, in the case where there is photogeneration - PL -, recombination will mostly take place in the region where light is absorbed. The light detected at energy E_G in the PL experiment is very likely to originate from the front emitter, where most of the laser light is absorbed. This may be the cause of the presence of peak A at room temperatures. On the contrary, when current is injected under dark conditions - EL - the greatest part of the recombination takes place in the regions with lower lifetimes and in the space charge region. In our case this implies that in the EL spectrum we are seeing mostly the luminescence produced in the QD material. This is why this technique allows an indirect yet strong coupling between the emission at energy E_G and the presence of a large QFL split between the CB and the IB. From these results we can conclude that EL measurements are more reliable than PL measurements to evaluate unambiguously the behaviour of complete IBSC devices. PL could give alternative information if used on specifically grown test samples without an emitter and likely required with surface passivation.

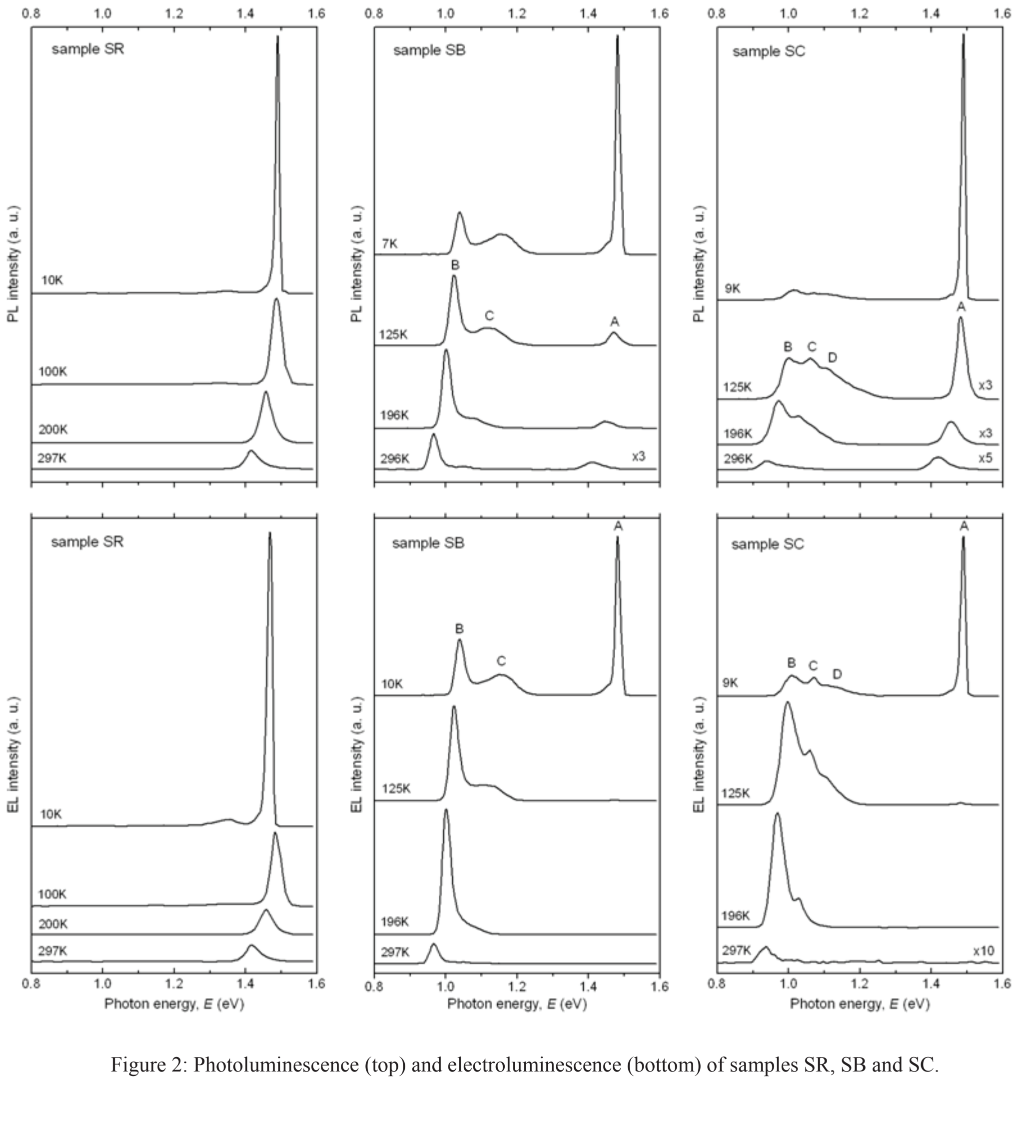

Figure 2: Photoluminescence (top) and electroluminescence (bottom) of samples SR, SB and SC.

4. Conclusions

Luminescence spectra render valuable information for the analysis of IBSCs, as they reveal the dynamics of carrier relaxation between the different bands. In this work the temperature dependence of the PL and EL spectra of two InAs/GaAs QD-IBSCs have been studied. The EL spectra at room temperature are not in agreement with the IBSC model and they can be explained by a too fast carrier relaxation between CB and IB. However, at low temperatures that relaxation is slowed down and the results are consistent with a QFL split between those two bands as predicted by the IBSC model. PL spectra appear to be less useful for this kind of analysis than EL spectra since the luminescence of the emitter of the cell cannot be distinguished from that of the IB material.

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