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Investigation on the performances of multi-quantum barriers in a single quantum well solar cell

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Multi-quantum barriers (MQBs) has been introduced into a single quantum well (SQW) solar cell to prevent the photo-generated electrons in the quantum well from leaking into the *p*-side, and is therefore intended for a new method to reduce the dark current and thereby improving the overall spectral response of the quantum well solar cell. Here we report on the performances of the MQB by dark current and photoluminescence measurement. It is found that the leakage possibility of the photo-generated electrons in the SQW into *p*-side and thus the dark current is suppressed for solar cell with MQB compared with that without MQB. © *2005 Springer Science + Business Media, Inc.*

1. Introduction

The quantum well solar cell has been proposed as an approach to achieving a higher efficiency solar cell [1, 2]. The photo-generated carriers in the quantum wells need to escape and be swept out by the built-in electric field to form the expected photocurrent. How well the cell performs will depend on the carrier escape efficiency, which is in competition with carrier recombination in quantum wells and barrier regions that represent a form of loss with respect to the photocurrent output. Moreover, the electron escape out of the quantum well by tunneling through the confining barrier into the *p*-side will cause an increase in dark current and reduction in filling factor, which forms an undesirable electron flow. Therefore, high material quality with minimum non-radiative recombination losses at the quantum well hetero-interfaces and high electron escape rate of photo-generated carriers out of quantum well into *n*-side collector region are required.

To enhance the desirable electrons escape and reduce recombination losses in multi quantum well solar cell, Raisky and his colleagues [3] proposed a sequential resonant tunneling structure, where the multi quantum wells were designed so that electrons tunnel from the ground state of the jth well ($j = 1, 2, \ldots, N$) into an excited state of the $(j+1)$-th well, and then go on with intrasubband energy relaxation from the excited state to the ground state. This process was demonstrated to promote the electrons transmission and escape rate out of the multi quantum wells towards the built-in electric field direction, thus photocurrent was increased and recombination rate reduced. However, this sequential resonant tunneling structure is very complicated to be realized. Okada and his colleagues [4] proposed a tunnel barriers structure to block the photo-generated electrons in quantum well from leakage into *p*-side layers leading to dark current.

To block undesirable electron flow, a structure of multi quantum barriers (MQB) was confirmed to be an effective method. For example, MQB has already been successfully used in AlGaInP lasers to suppress electron leakage-related current which increases the threshold and lowers the characteristic temperature [5]. This is mainly attributed to better electron confinement due to quantum interference of the electrons within the MQB, creating a large increase of the barrier height at the waveguide–cladding interface and consequently suppressing the electron leakage current.

We have introduced MQB into a single quantum well (SQW) solar cell to prevent the photo-generated electrons in the quantum well from leaking into *p*-side and forming the undesirable electron flow, and then reduce the dark current and thereby improve the overall spectral response of the quantum well solar cell. Here we report on the performances of the MQB by dark current and photoluminescence measurement. It is found that the leakage possibility of the photo-generated electrons in the SQW into *p*-side and thus the dark current is suppressed for solar cell with MQB compared with that without MQB.

2. Device structure

The single quantum well solar cell (SQWSC) with MQB is based on $Al_{0.5}In_{0.5}P$ p-i-n structure and schematically depicted in Fig. 1 (Note: the material

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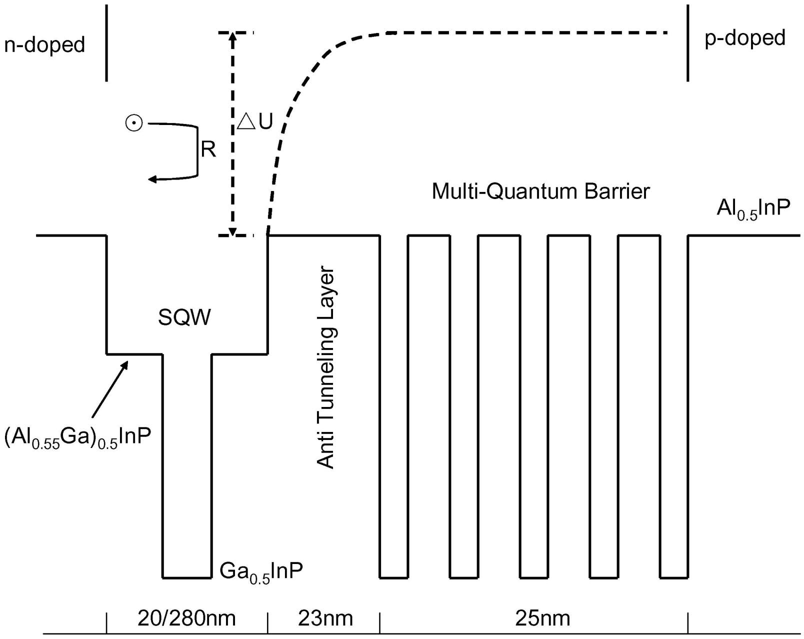

Figure 1 Structure of a single quantum well solar cell with MQB.

system of AlGaInP is not optimum for solar cell. The reason why it is chosen for this study is that our experience and our equipment are right in point). The single quantum well region is inserted in the middle of the i-region and consists of a 20 nm-thick $Ga_{0.5}In_{0.5}P$ single quantum well (SQW), which is sandwiched between two undoped 130 nm $(Al_{0.55}Ga_{0.45})_{0.5}In_{0.5}P$ confinement layers. On the p-doped side of $Al_{0.5}In_{0.5}P$ and just before the growth of the single quantum well region, a structure of MQB is grown. The MQB has a total thickness of 25 nm, where $Ga_{0.5}In_{0.5}P$ well is N monolayers (ML, and 1 ML = 0.283 nm) thick while $Al_{0.5}In_{0.5}P$ barrier M monolayers thick, thus the MQB is hereafter denoted as (N, M). To prevent photo-generated electrons in the quantum well from tunneling into the bound states of MQB, the first barrier of the MQB, i.e. the anti-tunneling layer is chosen as 23 nm thick. When designed correctly, the MQB structure will create a large increase of the barrier height at the interface between the SQW region and the MQB by ΔU [6] as marked in Fig. 1, and thus more electrons are blocked from leaking into p-side. All the samples are grown by low pressure metal organic vapor phase epitaxy (LP-MOVPE) in a horizontal reactor using standard precursors. Meanwhile, H_2Se and Cp_2Mg are used respectively as n- and p-type doping sources. In order to suppress natural superlattice ordering, a GaAs:P++ (001) wafer, deliberately mis-oriented 6° toward the (111)A crystallographyic direction, is used as a substrate of the device, and the growth rate is set to be very low to 0.3 nm/s to fine control the layer thickness of the MQB. The growth and the reproducibility of the layer dimensions were checked and will be reported elsewhere. Several samples, all the same but with different combination of (N, M), are grown and will be measured to find out a best one (optimal (N, M)) where the quantum interference of electrons within the MQB is realized. After growth, 0.2 mm^2 Ni/AuGe/Au alloy was used as the front Ohmic contact and Cr/Zn/Au alloy for the back for electric characterization.

To study on the performance of the MQB used in the SQWSC, two test structures for photoluminescence measurement are also grown using the same conditions, one of which is schematically shown in Fig. 2, where a second MQB was symmetrically inserted in the n-type side. The other test structure is almost the same as in Fig. 2 but without MQB (marked as sample BULK). In Fig. 2, if the MQB is designed with a optimal set of

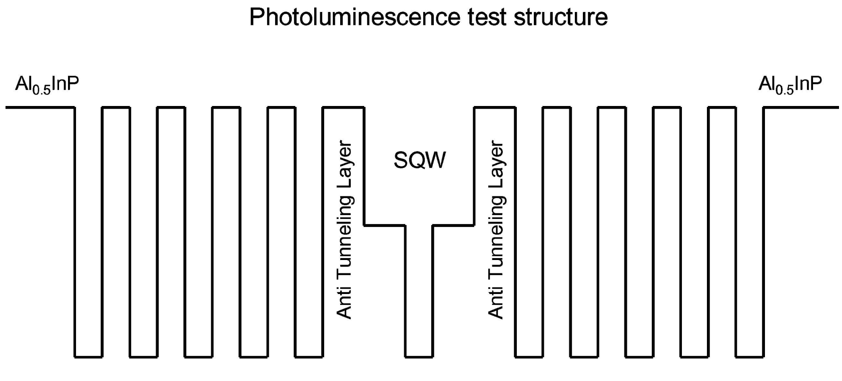

Figure 2 A test structure for photoluminescence study on the performance of MQB.

(N, M) where the requirement for the quantum interference of electrons within the MQB is met, the photoluminescence peak intensity of the sample under study should increase with excitation density and will saturate at an excitation density much higher than that for the sample BULK, and the correponding solar cell with the MQB of the optimal (N, M) should have lowest dark current.

3. Experiments and analysis

3.1. Dark current

In this material system, a good study on the performance of the MQB when used in a short wavelength AlGaInP laser has already been reported by Raisch [5], where the MQB, the same as studied here, was adopted to reduce thermal current losses or leakage current in the laser through the realization of the quantum interference of electrons within the MQB. On basis of the results reported there that (1, 11) is the best set of (N, M) with (1, 14), (2, 10) and (1, 9) next to the best, we chose to grow several samples which take on (N, M) as (1, 11), (1, 14), (2, 10) and (1, 9), respectively. For these samples, dark current at room temperature is measured, with an intention to find out the sample with optimal (N, M) in our study. The measurement results of dark current are shown in Fig. 3.

Fig. 3 shows the forward-bias voltage dependence of the dark current (dark I–V) for five samples, which are measured in dark at room temperature, where the line 1 represents the solar cell sample without MQB, line 2 for that with MQB of (1, 11); line 3 for with MQB of (1, 9); line 4 for with MQB of (1, 14) and line 5 for MQB of (2, 10). From this figure, it is obvious that the sample with MQB of (1, 14) is the optimal device, while keeping those with MQB of (1, 11) and (1, 9) being next to the optimal, which are almost within our expectation as in [5]. However, the sample with MQB of (2, 10) turned out to be worse than the sample without MQB in dark current. The reason for this is not clear and still under investigation. For samples with MQB of (1, 14), (1, 11) and (1, 9), we believe the improvements in dark current are due to the quantum interference of electrons within their respective MQB. The primary difference between these samples is that the difference between the increase of ΔU created by the quantum interference of electrons within the MQBs with different (N, M). The increase of ΔU for the sample with MQB of the optimal (1, 14) is the largest and thus the improvement in its dark current is the best.

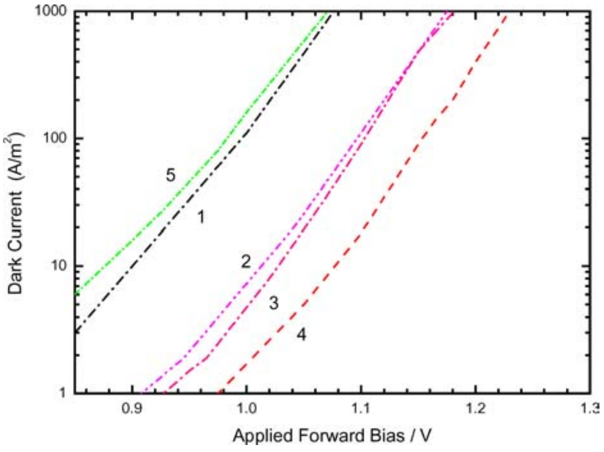

Figure 3 The dark current versus the forward-bias voltage for several solar cell samples. 1. without MQB; 2. (1, 11); 3. (1, 9); 4. (1, 14); 5. (2, 10).

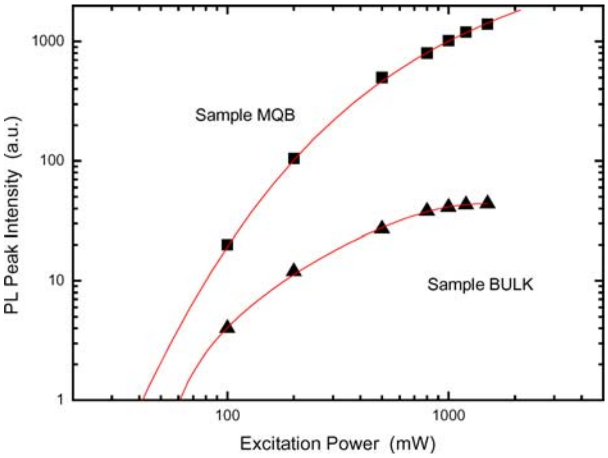

Figure 4 Excitation power dependence of the photoluminescence peak intensity at room temperature.

3.2. Photoluminescence

To confirm the results in dark current measurement, we make further study on the performance of MQB by photoluminescence (PL) measurement. For the photoluminescence measurement, the test sample with a pair of MQB as shown in Fig. 2 of optimal (1, 14) will be studied (hereafter marked as sample MQB), and for comparison, the sample BULK is also measured. Photoluminescence is measured at room temperature. The excitation light source is Ar$^+$ laser (488 nm), and the light beam is focused onto the sample surface with a spot size of 100 μmΦ.

Fig. 4 shows the excitation power dependence of the PL peak intensity for both sample MQB and sample BULK. Due to the effective mass of the holes being larger than that of the electrons in the SQW, we believe that the PL intensity from the SQW reveals the degree to which the electrons overflow the barrier from the SQW region to enhance the undesirable electron flow (dark current in solar cell). From Fig. 4, it is seen that the PL peak intensity of the sample MQB is greater than that of the sample BULK by about one order of magnitude [7]. To investigate the quantum interference of electrons within the MQB and its confinement effects on the electrons within the SQW, our interest focuses on the dependence of excitation power slope on PL peak intensity. From Fig. 4, one can see the intensity of the BULK sample reaches saturation faster than the MQB sample. For the sample BULK and when the excitation power is above 800 mW, the intensity is reaching saturation, while for the sample MQB and even when the excitation power reaches 1500 mW, the intensity is still showing an increase. We believe this reduced saturation behavior reveals a strong quantum interference of electrons existing within the MQB and a greater enhancement of the effective potential barrier height ΔU is created at the two interfaces between the SQW and the two MQBs of the sample MQB, respectively. This further confirms the results got in the dark current measurement that the solar cell sample with MQB of the optimal (1, 14) is greatly improved as compared with that without MQB. Therefore, the leakage possibility of the photo-generated electrons in the SQW into p-side and thus the dark current is suppressed for solar cell with MQB compared with that without MQB.

4. Conclusion

We have investigated the performances of multi quantum barriers when used in a single quantum well solar cell, which is intended for a method to prevent the photo-generated electrons in the quantum well from leaking into the p-side. This will reduce the dark current of the quantum well solar cell. In this paper, the results on the improvement in solar cell dark current characteristic due to the introduction of the multi quantum barriers were reported. Photoluminescence study reveals that a strong quantum interference of electrons is built within the MQB and then a great enhancement of the effective potential barrier height ΔU is realized at the interface between the single quantum well region and the region of the multi quantum barriers. Therefore, the leakage possibility of the photo-generated electrons in the SQW into p-side and thus the dark current is suppressed for solar cell with MQB compared with that without MQB. This is further confirmed by the dark current measurement. In conclusion, multi quantum barriers brings great improvements on the performance especially the dark current of the single quantum well solar cell through the realization of the quantum interference of electrons within it.

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