FABRICATION OF RESONANT TUNNELING STRUCTURES FOR SELECTIVE ENERGY CONTACT OF HOT CARRIER SOLAR CELL BASED ON III-V SEMICONDUCTORS

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ABSTRACT

In this study, double barrier (DB) resonant tunneling structures based on III-V semiconductors were fabricated and its potential for selective energy contacts (SEC) of hot carrier solar cells was evaluated. An AlGaAs/GaAs/AlGaAs quantum well (QW) based DB structure was fabricated by molecular beam epitaxy (MBE) on GaAs (001) substrate, which acts as SEC for electrons. The current-voltage (I-V) characteristics under light excitation shows a voltage shift of tunneling current tail to a lower bias and this result demonstrates an extraction of high energy photoelectrons through the DB structure. Furthermore, properties of quantum dot (QD) resonant tunneling structures were investigated as an ideal SEC. Photoluminescence (PL) measurements showed that controllable PL peak energy range of InAs QDs/$Al_xGa_{1-x}As$ structures well corresponds to the required carrier extraction energy, which is the difference between electron and hole extraction energies of SECs, for high conversion efficiency. In addition, resonant tunneling current peaks originate from the InAs QDs embedded in an $Al_{0.6}Ga_{0.4}As$ barrier are clearly observed for both forward and reverse bias by conductive atomic force microscope (C-AFM). These results indicate that InAs QD/$Al_xGa_{1-x}As$ resonant tunneling structures are suitable for designing the optimum SEC structure.

INTRODUCTION

A number of new concepts [1] for high efficiency photovoltaic conversion are recently studied to overcome the Shockley-Queisser limit of single gap solar cell [2]. Ross and Nozik proposed an idea of using hot carriers and showed that the conversion efficiency of over 60% under 1 sun illumination and over 80% under full concentration is theoretically achievable in such hot carrier solar cells [3]. One practical structure of a hot carrier solar cell is to use a photon absorbing layer, in which hot carriers are slowly cooled, sandwiched between two selective energy contacts (SEC) as schematically illustrated in Fig. 1 [4, 5]. A SEC is an energy filter allowing for carriers with specific energy to pass through and hot carriers are collected through the SEC. Double barrier (DB) resonant tunneling structures are considered to be a possible candidate for SEC. Several investigations on the basic properties of DB structures as SEC have been reported [6-8]. Conibeer *et al*. reported resonant tunneling properties of Si quantum dot (QD) based DB structures and they proofed the concept [6].The filtering energy level of SEC for carriers is sensitive on conversion efficiency, and thus, precise control of the resonant energy of a DB structure is essential for its application. From this point of view, we have focused on DB resonant tunneling structures based on III-V semiconductors because their variety of material combination enables to design optimum energy configuration with keeping high material quality. In this study, we fabricate DB structures based on III-V semiconductors and discuss their potential for SEC of hot carrier solar cells.

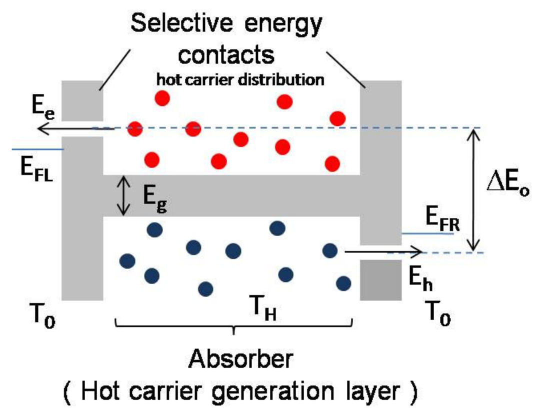

Figure 1 Schematic band structure of a hot carrier solar cell.

EXPERIMENTAL

All the samples used here were fabricated on n-type GaAs(001) substrates by atomic hydrogen-assisted molecular beam epitaxy (H-MBE) [9]. Preliminary demonstration of hot carrier generation and collection through a DB resonant tunneling structure is carried out by measuring current-voltage (I-V) properties under light illumination. The concept of the experiment is schematically shown in Fig. 2. Photo-excitation by high energy photons generates hot electrons in the emitter region of resonant tunneling structure. High energy electrons can resonate to the quantum level with a smaller bias voltage compared to lower energy electrons and thus generation of hot electron distribution leads to extension of tunneling current tail towards lower voltages in the I-V curve. For that purpose, an $Al_{0.6}Ga_{0.4}As/GaAs/Al_{0.6}Ga_{0.4}As$ DB structure was prepared. Lightly doped n-type GaAs was grown on the DB structure as emitter region. A AuGe/Ni contact with a window area of 0.0025 mm^2 for light illumination was evaporated on the top surface and mesa etching was carried out for device separation. The collector contact was made on the back side of the substrate with In paste. A pulsed excitation was done with a laser diode with an emission wavelength of 643 nm or 805 nm. The frequency of pulsed excitation was kept at 520 Hz. A current increase caused by excitation was detected by a lock-in-amplifier. Emission power was adjusted in such a way that photon flux on the sample surface was $2x10^{19}$ $s^{-1}cm^{-2}$.

As an ideal SEC, QD-based DB structures were fabricated in which self-assembled InAs QDs were embedded in $Al_xGa_{1-x}As$ barriers. Before QD fabrication, an $Al_xGa_{1-x}As$ layer was deposited at a substrate temperature of 580°C. Then the substrate temperature was decreased to 520°C and 2 ML InAs was supplied on the growing surface to form QDs on the $Al_xGa_{1-x}As$ layer. QD formation was confirmed by *in-situ* reflection high energy electron diffraction (RHEED) during growth. The substrate temperature was kept at 520°C during the following deposition of 5 nm $Al_xGa_{1-x}As$ cap and increased again to 580°C for further deposition of $Al_xGa_{1-x}As$. The optical properties of QD-based DB structures were evaluated by photoluminescence (PL) spectroscopy. The PL signal was detected by using an optical multi-channel analyzer system with a Si CCD detector and a $Nd:YVO_4$ laser with ~15 mW at 532 nm was used for the excitation source. In addition, carrier tunneling through QD was observed by conductive atomic force microscopy (C-AFM). In the C-AFM measurements, samples were kept at -120°C and bias voltage was applied from the back side of the samples while the conductive AFM tip was electrically grounded.

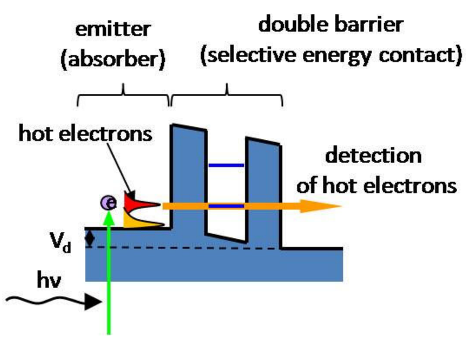

Figure 2 A schematic illustration of photo-generation of hot carrier distribution and its extraction through a DB resonant tunneling structure.

RESULTS AND DISCUSSION

Figure 3 shows the current increase induced by light excitation versus the applied bias voltage of the QW-based DB structure measured at 77K. Current peak structures due to electron resonant tunneling were observed around the bias voltage of 3.5 V in the I-V curves. A voltage shift of tunneling current tail to lower bias is clearly observed with higher energy excitation compared to lower energy excitation. The electrons were excited to the conduction band of absorbing layer (GaAs) at ~360 meV and ~10 meV above the band edge by 643 nm and 805 nm excitation, respectively. The electrons excited in the absorber lose a part of excess energy during their transportation to the edge of the absorber. An estimation by Monte-Carlo simulation taking into account scattering processes of electrons with impurities and phonons revealed that excited electrons with initial excess energy of 300-400 meV can be extracted from the absorber with the remaining energy of 100-200 meV if the width of the absorber is within the range of a few hundred nm [8]. The observed voltage shift of the tunneling current tail is well consistent with the calculated energy range, and thus, this result demonstrates an extraction of optically generated high energy photocarriers through the DB resonant tunneling structure.

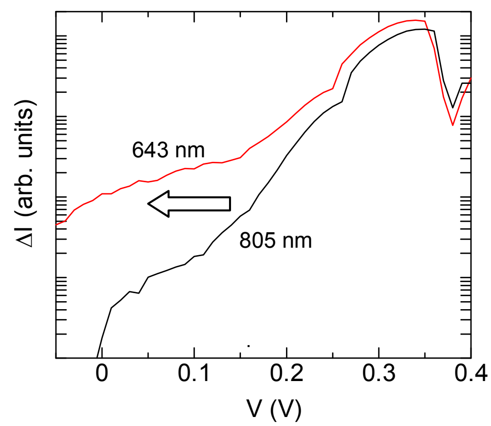

Figure 3 Dependence of the current increase induced by light excitation on applied voltage. The excitation wavelengths are 643 nm (red line) and 805 nm (black line).

A resonant tunneling scheme using QDs should be more suitable for SEC because of its ideal energy selectivity, and for this purpose, self-assembled InAs QDs embedded in $Al_xGa_{1-x}As$ barrier layers were fabricated. For PL measurement, InAs QDs were grown on 60 nm-thick $Al_xGa_{1-x}As$ layer followed by 65 nm-thick $Al_xGa_{1-x}As$ capping. Al composition of the barrier layers was changed from 0 to 0.6. QD formation was confirmed during MBE growth for all the Al compositions by transition of RHEED patterns from streak to spot. Figure 4 shows the PL spectra at 77K for various Al compositions of the barrier layers. The PL peak energy of QDs was controlled from 1.2 eV to 1.6 eV by changing the Al composition from 0 to 0.6. Figure 5 shows the dependence of theoretical conversion efficiency of a hot carrier solar cell and required carrier extraction energy ΔE_o, which is the difference between electron and hole extraction energies (see Fig. 1), on the energy gap of absorber calculated by detailed balance model [3, 10]. As the result indicates, ΔE_o is needed to be in the range from 1.3 eV to 1.7 eV for obtaining efficiencies higher than 60% under 1 sun and 80% under full concentration. The experimentally obtained

PL peak energy range of InAs QDs/$Al_xGa_{1-x}As$ structures well corresponds to the required ΔE_o for high conversion efficiency. For hot carrier solar cell operation, generated photocarriers only in a small energy range δE, which is ideally much smaller than kT, at a selective energy level of SEC have to be extracted [3, 4]. In this case, δE corresponds to the distribution of the resonant energy level of QDs. However, the FWHM of the PL peaks are much larger than kT. More improvement in size uniformity of QDs is essentially needed.

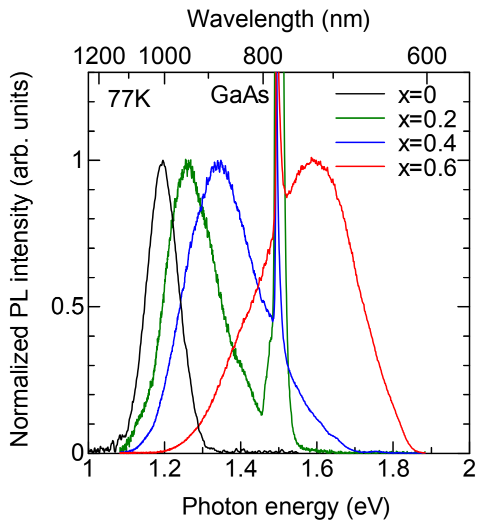

Figure 4 PL spectra of InAs QDs embedded in $Al_xGa_{1-x}As$ barrier layers. The intense luminescent peaks at 1.50 eV are from GaAs substrates.

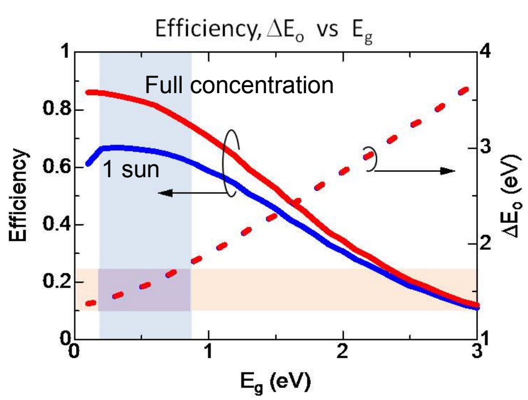

Figure 5 Detailed balance model calculation of the conversion efficiency and required ΔE_o vs bandgap energy of absorber.

In order to observe QD resonant tunneling, I-V property was measured by C-AFM. The sample was grown on n-type substrates and InAs QDs were embedded in the middle of $Al_{0.6}Ga_{0.4}As$ layer with a thickness of 17 nm. Another InAs QDs layer was formed on the top layer to form an ohmic contact with metal-coated AFM tips. Figures 6 show the I-V curves measured at several positions on the sample surface. In the figures, current is shown as absolute value. Resonant tunneling current peaks originate from the embedded InAs QDs were clearly observed for both forward and reverse bias. Although relatively broad current peaks appear in the curves and they are possibly due to tunneling current contributed from several QDs beneath the AFM tip, several resonant tunneling are found as very sharp current peaks. This represents that resonant tunneling *via* individual QD intrinsically allow carriers in a very narrow energy range to path through. These results thus indicate that InAs QD/$Al_xGa_{1-x}As$ resonant tunneling structures are suitable for designing the optimum SEC structure.

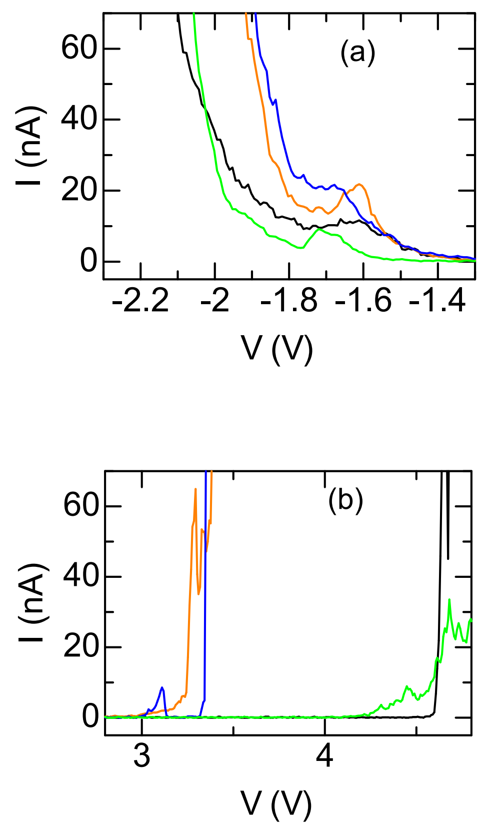

Figure 6 I-V characteristics of InAs QDs embedded in $Al_{0.6}Ga_{0.4}As$ barriers measured by C-AFM. (a) reverse bias and (b) forward bias. Bias voltage was applied from the substrate to the AFM tip. Current is shown as absolute value in the figures. Each curve indicates a measurement result at different positions on the sample surface.

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CONCLUSION

DB resonant structures based on III-V semiconductors were fabricated and their potential as SEC of hot carrier solar cells was investigated. An AlGaAs/GaAs/AlGaAs DB quantum well structure fabricated by MBE on GaAs (001) substrate was characterized by I-V measurements under light excitation. Higher energy excitation of photoelectrons leads to a voltage shift of tunneling current tail to a lower bias and this result demonstrates an extraction of high energy photoelectrons through the DB structure. Furthermore, properties of QD resonant tunneling structures were investigated as an ideal SEC. PL measurements showed that controllable PL peak energy range of InAs QDs/$Al_xGa_{1-x}As$ structures are in good agreement with the required carrier extraction energy, which is the difference between electron and hole extraction energies of SECs, for high conversion efficiency. In addition, resonant tunneling originate from the InAs QDs embedded in an $Al_{0.6}Ga_{0.4}As$ barrier was clearly observed as sharp current peaks in the I-V curves measured by C-AFM. This result represents that resonant tunneling *via* individual QD intrinsically allow carriers in a very narrow energy range to path through. These features of InAs QD/$Al_xGa_{1-x}As$ resonant tunneling structures indicate their suitability for SEC of hot carrier solar cells.

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