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Nanoscale engineering of photoelectron processes in quantum well and dot structures for sensing and energy conversion

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Abstract. Advanced selective doping provides effective tool for nanoscale engineering of potential barriers and photoelectron processes in quantum well (QW) and quantum dot (QD) optoelectronic nanomaterials for IR sensing and wide band photovoltaic conversion. Photoelectron kinetics and device characteristics are investigated theoretically and experimentally. Asymmetrical doping of QWs is employed in a double QW structure for tuning electron transitions in QWs by voltage bias. These QW devices demonstrate bias-tunable multi-color detection and capability of remote temperature sensing. The QD structures with bipolar doping are proposed to independently control photocarrier lifetime (photocurrent) and dark current. The bipolar doping allows us to increase the height of nanoscale potential barriers around QDs without changing the electron population in QDs, which determines dark current. The QD devices with bipolar doping demonstrate significant enhancement of photocurrent, while dark current is close to that in corresponding reference devices with unipolar doping.

1. Introduction

With the advancement of material growth technology, semiconductor nanomaterials offer numerous opportunities for developing advanced optoelectronic devices. Nanostructures with quantum wells (QWs) and quantum dots (QDs) provide high degree of flexibility for engineering of band structure and nanoscale potential barriers. Selective doping in QW and QD nanomaterials allows us to control the nanoscale potential profile, created by charged QWs and QDs, and, in this way, to optimize photoelectron processes for enhanced sensing and photovoltaic conversion [1-4].

Here we present our recent results on advanced QW and QD nanomaterials with specific selective doping. In Section 2, we investigate asymmetrical doping of GaAs/AlGaAs double quantum wells (DQW) structures. Such doping enhances bias-induced charge redistribution between wells, which, in turn, modifies electron transitions in QWs. As a result, these DQW structures demonstrate significant tunability of spectral photoresponse characteristics, which can be effectively controlled by changing the polarity and/or magnitude of voltage bias. In Section 3, we report results of our studies of selective bipolar doping in QD structures. The bipolar doping combines the p-type doping in QD layers with the acceptors, N_A, and the n-type doping of inter-dot layers with donors, N_D. The number of free electrons

in populated QDs is proportional to $N_D - N_A$. Population of QDs determines the dark current and, therefore, the dark current is also proportional to $N_D - N_A$. The potential barriers around dots are determined by the electron charge in QDs that is proportional to N_D. The potential barriers strongly suppress photoelectron capture and increase photoelectron lifetime.

2. Asymmetric doping of double quantum wells

Asymmetrically doped DQW structures were grown on semi-insulating GaAs wafer to permit backside illumination. The growth sequence started with a 500 nm undoped GaAs buffer layer, and was followed by a 800 nm heavily-doped ($N_D = 2 \times 10^{18}$ cm^{-3}) GaAs contact layer, 25 stages of the detection unit, a 400 nm heavily-doped ($N_D = 2 \times 10^{18}$ cm^{-3}) GaAs contact layer, and finally 5 nm InGaAs layer doped to 10^{19} cm^{-3}. One DQW unit is composed of a 6.5 nm GaAs layer doped by Si with sheet density 5×10^{11} cm^{-2} and 6.5 nm layer of undoped GaAs. They are separated by a 3.1 nm thick Al$_{0.2}$Ga$_{0.8}$As barrier. The DQW units are separated by 50 nm Al$_{0.2}$Ga$_{0.8}$As barriers. Grown structures were processed by standard photolithography, wet chemical etching, and metallization techniques.

2.1. Tunable characteristic of multi-color detection

In single quantum well infrared photodetector (QWIP) device, it is known that dark current at positive bias is usually higher than that at corresponding negative bias due to the dopant migration in the growth direction. In Fig. 1, dark current in our DQW devices is practically symmetrical with respect to applied bias. This is because the dopant migration is essentially compensated by asymmetrical doping in our DQW structures.
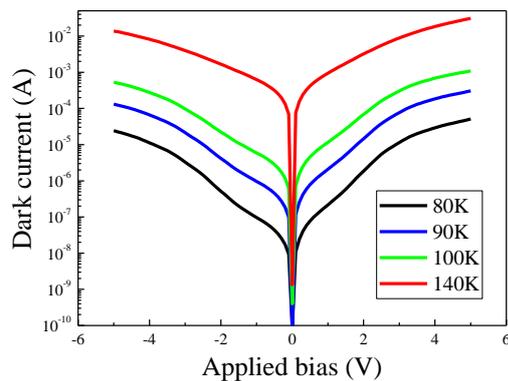

Figure 1. Dark current of QWIP based on asymmetrically doped DQW structures at 80K, 90K, 100K and 140K. They are measured by Keithley 2602 source-meter with grounded bottom contact.

The asymmetrical doping in DQW structure enhances bias-induced charge redistribution. As a result, these structures demonstrate significant tunability of electron transitions in DQW and corresponding tunability of spectral photoresponse. In Fig. 2, the detection peak varies from 7.5 μm to 11.1 μm when moderate voltage bias applies. It demonstrates that spectral photoresponse strongly depends on magnitude and polarity of applied bias due to induced electron charge redistribution. Tunable spectral characteristics are very attractive for adaptive IR sensing in complex environment.
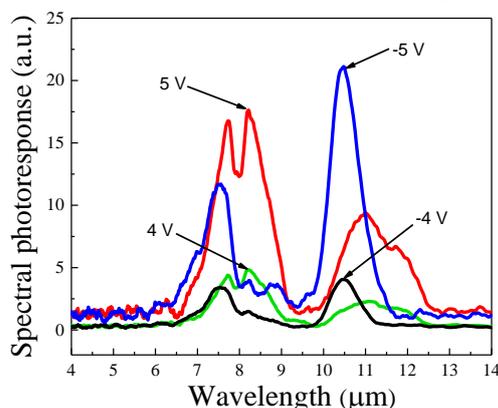

Figure 2. Spectral dependency of photoresponse in QWIP at T = 80K under positive bias 4 V, 5 V and negative bias -4 V, -5 V. Spectral photoresponse is recorded by VERTEX 70 FTIR spectrometer integrating SR570 low-noise current preamplifier.

2.2. Remote temperature sensing

In order to evaluate the capability of temperature sensing in our devices, we investigate the dependency of photocurrent on object temperature theoretically and experimentally. The modeling photocurrent is the integral of product of incident power and device responsivity over corresponding wavelength range. The experimental photocurrent is straight measured by current amplifiers using standard blackbody radiation. As shown in Fig. 3 (a), it demonstrates a good agreement between normalized modeling and experimental photocurrent, and they both strongly depend on object temperature.
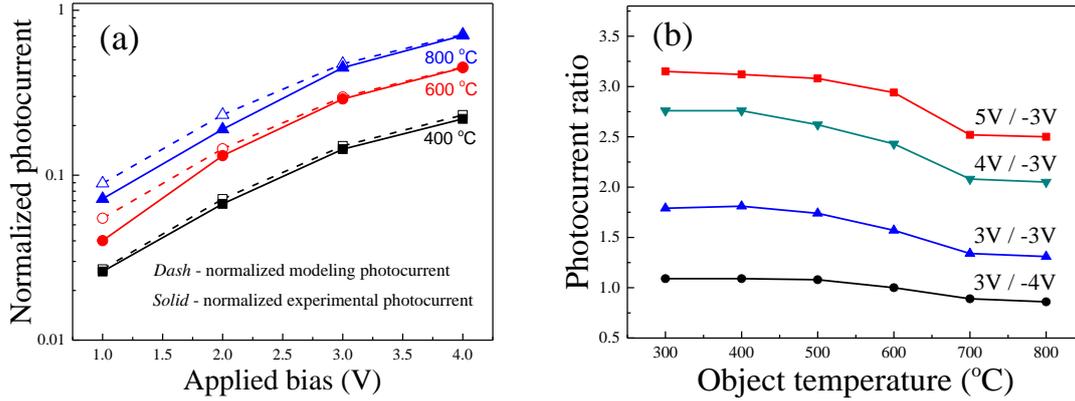

Figure 3. (a) Normalized modeling and experimental photocurrent at 400°C, 600°C and 800°C. (b) Photocurrent ratio as a function of object temperature.

Object temperature is not the only factor that determines thermal radiation. Emissivity and geometrical factor also affect its characteristic. Single-color photodetector cannot determine object temperature by simply measuring photocurrent, because it is difficult to eliminate the effects of emissivity and geometrical factor. However, multi-color photodetector is capable of determining object temperature because the ratio of photocurrents at two biases from the same device is only a function of object temperature, according to Eq. (1). It is also experimentally verified in Fig. 3 (b).

$$r(T) = \frac{I_{pc1}}{I_{pc2}} = \frac{\varepsilon g \int B(\lambda,T) \cdot R(\lambda,V_1) d\lambda}{\varepsilon g \int B(\lambda,T) \cdot R(\lambda,V_2) d\lambda} = \frac{\int B(\lambda,T) \cdot R(\lambda,V_1) d\lambda}{\int B(\lambda,T) \cdot R(\lambda,V_2) d\lambda} \tag{1}$$

3. Enhanced nanoscale potential profile around quantum dots

The key challenge in improving the performance of quantum dot IR photodetector (QDIP) is the trade-off between photocurrent and dark current. As two currents share the common path of electron transitions, high doping level increases the photocurrent, but inevitably leads to higher dark current. In order to independently control the photocurrent and dark current, we propose bipolar doping in QD structures. It combines p-type doping in QD layers with the acceptors, N_A, and n-type doping in inter-dot layers with donors, N_D.

The dark current is given by

$$J_{dc} = eN_{th}/\tau_{tr} = en_{th}S/\tau_{tr} \propto (N_D - N_A) \tag{2}$$

where n_{th} is thermally generated carrier, S is the device square and τ_{tr} is the electron transit time.

The photoelectron lifetime is exponentially increased due to potential barriers around negatively charged quantum dots

$$\frac{1}{\tau_l} = \pi n_D a^3 \frac{1}{\tau_\varepsilon} \exp[-e\phi(Q)/kT] \propto \exp(-\frac{\phi(N_D)}{kT}) \tag{3}$$

where n_D is dot concentration, a is QD radius, $1/\tau_\varepsilon$ is inelastic electron-phonon relaxation rate, and ϕ is the potential at the dot boundary.

In the experiment, we design sample 4e0p ($N_D = 4$) with unipolar n-type doping outside of dots that supply on average 4 electrons per dot, and sample 7e3p ($N_D = 7$, $N_A = 3$) with n-type doping outside of

dots that supply on average 7 electrons pet dot and p-type doping in QD layers that bind about 3 electrons per dot to retain the same number of free electrons per dot. Results are presented in Fig. 4. In Fig. 4 (a), photocurrent in 7e3p is improved by 25% compared with 4e0p, but they have the close dark current. It is in good agreement with Eq. (2) and Eq. (3) where dark current is proportional to N_D - N_A and photoelectron lifetime (photocurrent) is proportional to N_D. In Fig. 4 (b), the voltage dependency of responsivity demonstrates the strong enhancement of photocurrent due to bipolar doping.
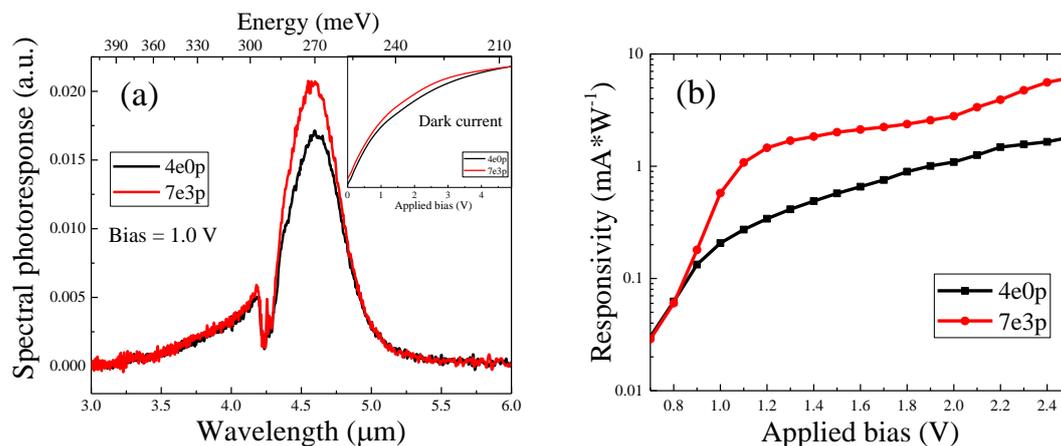

Figure 4. (a) Spectral photoresponse of 4e0p and 7e3p at 1.0 V and 80 K. The inset shows dark current. (b) Responsivity as a function of applied bias at 80 K.

4. Conclusions

We investigated the effects of nanoscale engineering for managing photoelectron processes in quantum well and quantum dot nanomaterials by employing selective doping. In our quantum well infrared photodetector devices, the asymmetrical doping between double QWs creates bias-induced charge redistribution between QWs. Due to the charge redistribution the bias-dependent photoresponse peak can vary from 7.5 µm to 11.1 µm depending on the polarity and/or magnitude of bias. Also, the photocurrent ratio is only a function of object temperature, which provides capability of remote temperature sensing. In quantum dot infrared photodetector (QDIP) structures, the bipolar doping is theoretically and experimentally proved to provide independent managing of photocarrier lifetime (i.e. photocurrent) and dark current. In particular, the device with 7e3p bipolar doping shows strongly enhanced photocurrent and practically the same dark current as the device with 4e0p unipolar doping. Thus, due to longer photoelectron lifetime the bipolar doping increases the sensitivity of QDIPs.

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