Transport characteristics of InAs/GaAs quantum-dot infrared photodetectors

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A ten-stacked self-assembled InAs/GaAs quantum dot (QD) infrared photodetector is investigated. A wide detection window of 2–10 μm is observed with a peak responsivity of 187 mA/W at 7 μm under an applied voltage of 1.1 V. The observed negative differential conductance (NDC) of the photocurrent at low temperature is attributed to the formation of high-field domains and the resultant intervalley scattering in the GaAs barrier layer. The disappearance of the NDC and the increase of single-QD photoluminescence intensity with increasing temperature below 100 K are attributed to the thermally assisted electron redistribution with increasing temperature. © 2003 American Institute of Physics. [DOI: 10.1063/1.1594285]

Self-assembled InAs quantum dots on the GaAs substrate prepared by molecular beam epitaxy (MBE) have attracted much attention in recent years.^{1–5} Due to its long carrier capture and relaxation times,⁶ the quantum dot structure is suitable for the application of the infrared photodetector. Although a lot of effort had been devoted to the fabrication of quantum dot infrared photodetector (QDIP),^{7–9} detailed discussions on the transport mechanisms of the device are still unavailable. In this letter, current conduction through a ten-stacked InAs/GaAs QDIP is investigated. Transport mechanisms of the device are analyzed based on the voltage-dependent photocurrent and activation energies derived from temperature-dependent dark current.

The self-assembled InAs quantum dots were grown on a (100) GaAs substrate under an arsenic shutter closed condition by VG 80H solid source MBE at 510 °C. The atomic force microscopic (AFM) image and corresponding photoluminescence (PL) spectrum of a single 3 ML InAs dot layer measured at 10 K are shown in Fig. 1. The dot density is $4 \times 10^{10} \text{ cm}^{-2}$ with an average height of 6 nm and the PL peak locates at 1.15 eV which is similar to the result of another report.⁵ As shown in the AFM image of Fig. 1, two-sized dot distributions are observed. InAs QDs with a smaller size are about 40 nm×39 nm in size and 6.0 nm in height and the larger ones are 78 nm×50 nm in size and 10.5 nm in height. Therefore, it is assumed that the vertical direction is the main quantization direction. Sandwiched between a 0.5 μm top and 1 μm bottom GaAs contact layer with Si doped to $1 \times 10^{18} \text{ cm}^{-3}$, ten periods of a 3 ML InAs QD and a 30 nm GaAs barrier are grown under the same growth condition as the single QD sample. The InAs QD is uniformly doped to $1 \times 10^{18} \text{ cm}^{-3}$. After a two-step process, a 100×100 μm^2 device is fabricated. The TE/TM mode responsivity of the device is measured under edge-coupling scheme with APD cryogenics and a Perkin-Elmer S2000 Fourier-transform infrared spectroscopy, which is a standard procedure for QWIP measurement.^{10,11} By carefully shielding the device from the background infrared radiation, dark

I – V curves are measured with a HP4145A semiconductor parameter analyzer.

The spectral response curves under both positive and negative biases at 20 K are shown in Fig. 2. The positive bias means the positive voltage is applied to the top GaAs contact layer. The peak responsivity of the detector is at 7 μm under negative (–1.2 V) and positive (1.1 V) biases with the values of 105 and 187 mA/W, respectively. Although severe moisture absorption is observed at this wavelength region, it is possible to shift the detection windows of the QDIP to a middle (3–5 μm) and a long (8–14 μm) wavelength by varying the active region from an InAs QD to an InGaAs QD or capping an InGaAs strain relaxation layer onto InAs QDs.^{7,12} Another feature of the response curve would be the broadband property of the QDIP. The spectral broadening $\Delta\lambda/\lambda_p$ (3.5 $\mu\text{m}/7 \mu\text{m}$) of the device is 50% which is compatible or even larger than the specially designed QWIP.^{13–14} Under the quantum well approximation the conduction band discontinuity is to be 0.83 eV,¹⁵ energy levels are calculated according to the actual thickness of the quantum dot, which is shown in the inset of Fig. 2. The photoresponse of the detector is attributed to the E_2 -continuum transition with the corresponding wavelength 6.36 μm . And under the assumption of charge neutrality and on-center hydrogenic donor, the

FIG. 1. 10 K PL spectrum of 3 ML InAs quantum dots grown on a GaAs substrate. The inset shows the $1 \times 1 \mu\text{m}^2$ AFM image.

FIG. 2. Spectral response of a QDIP under both positive and negative biases at 29 K and the inset shows the calculated energy levels.

Fermi level of the structure derived is just beneath the first confined state.

Derived through temperature-dependent dark currents shown in Fig. 3(a), the dark current at fixed bias is given by $I_D = A\sigma\epsilon$, where A is the cross section, σ is the conductivity, and ϵ is the fixed electric field. Since conductivity is limited by impurity scattering at low temperature

$$\sigma = BT^3 e^{-E_a/kT}, \quad (1)$$

where T is the temperature, E_a is activation energy which equals to $(\Delta E_C - E_F)$. ΔE_C is the conduction band discontinuity and E_F is the Fermi level. The derived activation energies under different biases are shown in Fig. 3(b). It is shown that the zero-bias activation energy is 173 meV, which according to our calculation, corresponds to the Fermi level being located at 0.66 eV slightly higher than E_2 state, i.e., 0.633 eV. According to the fitting result, the zero-bias band diagram across the QDs is shown in Fig. 3(c). The excess carriers are injected from the top and bottom (n^+) GaAs contact, which provide the major source for photoexcitation instead of the background doping. With the presence of an external electrical field, the transit time of photoexcited electrons in the GaAs layer decreases and the photoconductivity increases dramatically with increasing bias as shown in Fig. 2. And the broadening of the confinement state E_2 due to size variation of QDs gives rise to broad spectra.

By integrating the response curves at 20 and 100 K, the relative photocurrent intensity under different biases is shown in Fig. 4. The photocurrent increases with increasing bias. However, for bias beyond 1.1 and -1.2 V at 20 K, the photocurrent begins to decrease with increasing bias. This negative differential conductance (NDC) disappears as the device temperature rose up to 100 K as shown in Fig. 4.

To explain the NDC of the QDIP, the decrease of photocurrent is attributed to the intervalley scattering of photoelectrons from Γ to L or X valleys when transporting across the GaAs barrier. When the scattering occurs, the electron momentum will be randomized such that the electron mobility in the barrier will decrease resulting in the decrease of photoresponse. The calculating results show that the critical voltage for the intervalley scattering to occur would be 350 mV, i.e., mean free path per scattering. Assuming uniform electrical-field distribution, the critical voltage for the NDC to occur would be over 3 V which is much larger than observed 1.1 and -1.2 V. The reason lies on the formation of high-field domain in the QD structure. As temperature in-

FIG. 3. (a) Temperature-dependent dark currents, (b) activation energies derived from curve fitting of dark current under different biases, and (c) zero-bias band diagram (across the QDs) of the ten-stacked QD device.

creases, the thermal-assisted electron redistribution would eliminate the high field region and result in more uniform distribution of a potential drop over the structure and the NDC disappears as shown in Fig. 4. Also shown in Fig. 4 is the increase of the photocurrent with increasing temperature

FIG. 4. The photocurrent of a QDIP as a function of applied biases at 20 and 100 K.

below 100 K. For temperature higher than 100 K, the photocurrent would drop due to the increase of phonon interaction, which is similar to the increase of single QD PL intensity until ~ 100 K.¹⁶

In conclusion, through the analysis of photocurrent of the QDIP under different biases, the formation of high-field domain in the QD structure and the resultant intervalley scattering are responsible for the NDC to occur under low temperature and small applied voltage. And from the analysis of temperature-dependent dark current, the carriers in the InAs quantum dots are found to come from (n^+) GaAs contact layers.

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