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Bias and temperature dependence of the escape processes in quantum dots-in-a-well infrared photodetectors

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The performance of quantum dots-in-a-well infrared photodetectors (DWELL IPs) has been studied by means of interband and intersubband photocurrent measurements as well as dark current measurements. Using interband photocurrent measurements, substantial escape of electrons from lower lying states in the DWELL structure at large biases was revealed. Furthermore, a significant variation in the escape probability from energy states in the DWELL structure with applied bias was observed. These facts can explain the strong temperature and bias dependence of both photocurrent and dark currents in DWELL IPs. © 2008 American Institute of Physics. [DOI: 10.1063/1.2977757]

Infrared photodetectors (IPs) have gained a lot of attention during the past decades due to the numerous applications in night vision, space, surveillance, search and rescue, and medical diagnosis. One state-of-the-art realization of this detector type is the quantum well infrared photodetector (QWIP) in which intersubband transitions provide the optical signal. A further development of these detectors is the quantum dot infrared photodetector (QDIP), with intersubband transitions from the ground state to excited states of the quantum dots (QDs) as the main detection mechanism. In QDs, the charge carriers are confined in three directions, resulting in a discrete energy level spectrum, which will limit the number of allowed transitions. Consequently, an enhanced detector performance is expected with lower dark current and increased sensitivity to incident light of all angles of incidence.¹ Decreased dark current, which enables operation at higher temperatures, has been realized by means of QDIP structures by several research groups in the medium wavelength infrared (3–5 μm) region^{2–4} but more rarely in the long wavelength infrared (LWIR) (8–12 μm) region.⁵ In order to enable tailoring of the detection wavelength in the LWIR detection region, a new class of QD based detectors, so-called quantum dots-in-a-well (DWELL) IPs, have been developed.^{6–8} In these detectors, a transition from the QD ground state to a final state in the surrounding quantum well (QW) and subsequent tunneling out of the well result in a photocurrent. DWELL IPs offer an extended tunability of the detection wavelength through adjustment of the size and composition of both the QW and QDs. High detectivity has been reported for DWELL IPs in the LWIR region,⁷ and focal plane arrays have been realized with a low noise equivalent temperature difference.⁶ However, a proper design of the DWELL structure is necessary in order to fully gain the predicted advantages of QD based IPs.

In this article, we present results that improve the understanding of the electronic processes that determine the per-

formance of DWELL IPs. From studies of the responsivity and dark current as a function of temperature and bias, it is shown that the performance achieved with the DWELL IP design is strongly dependent on the escape processes from the QW. This is demonstrated by interband and intersubband photocurrent measurements, revealing the escape probability from different energy states, with the applied bias as variable parameter. These measurements unravel important mechanisms contributing to the photocurrent and dark current.

The DWELL IP structure employed in this study consisted of a QD active region, sandwiched between an upper and a lower n -doped ($\sim 1 \times 10^{17} \text{ cm}^{-3}$) contact layer, with thicknesses of 300 and 500 nm, respectively. The active region in the DWELL IP structure was a ten-layer stack, where each period consisted of an undoped InAs QD layer embedded asymmetrically in an 8 nm $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ QW (with 2 nm InGaAs under and 6 nm InGaAs above the QD layer). The periods were separated from each other by a 33 nm thick GaAs barrier layer. Details about the growth conditions have been described in earlier publications.^{9,10} From atomic force micrographs, the QD density and the average QD diameter and height have been estimated to be $9 \times 10^{10} \text{ cm}^{-2}$, 16 nm, and 3.5 nm, respectively. The vertical DWELL IP structure was fabricated by standard optical lithography, etching, and metallization techniques. A square $360 \times 360 \mu\text{m}^2$ single pixel component with alloyed AuGe/Ni/Au Ohmic contacts was used for the photocurrent and dark current measurements.

The *interband* and *intersubband* photocurrent measurements were performed with a Bomem DA8 Fourier Transform spectrometer, in combination with a Keithley 427 current amplifier. A quartz-halogen tungsten lamp and a quartz beam splitter were used when measuring interband photocurrent, while a global light source and KBr beam splitter were used for intersubband photocurrent measurements. The sample was excited by unpolarized light at normal incidence. In the photocurrent measurements, a positive bias was applied to the bottom contact of the detector. Responsivity values have been deduced through reference measurements in a

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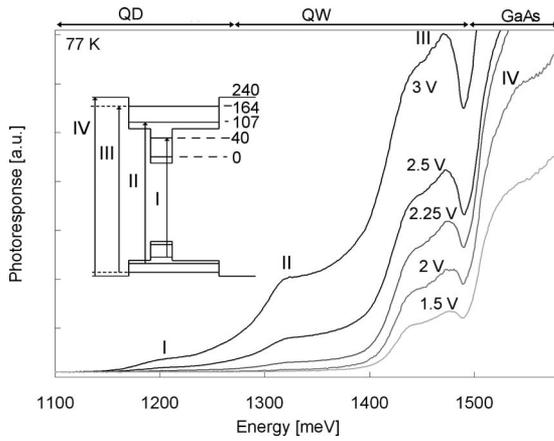


FIG. 1. Measurements of the interband photocurrent showing the bias dependence at a temperature of 77 K. In the inset the interband transitions corresponding to the photocurrent peaks are shown, as well as a tentative energy level scheme for the conduction band.

calibrated setup consisting of a blackbody source, a monochromator, a lock-in amplifier, and a Keithley electrometer. Dark current measurements were performed with a Keithley electrometer in a dark shielded cryostat. Due to positive biasing of the detector in the photocurrent measurements, only the dark current dependence for positive biases will be discussed.

The origin of the peaks observed in the interband photocurrent measurements (Fig. 1) has earlier been identified¹¹ employing Fourier transform photoluminescence (FTPL) and FTPL excitation (FTPLE) measurements. Using the conduction band energy level structure (inset, Fig. 1) derived from the FTPL and FTPLE measurements in a similar manner as in Ref. 11, the peaks observed in the intersubband photocurrent measurements were attributed to the transitions from the QD ground state to a QW excited state and the GaAs barrier, respectively [peak *i* and *ii* in Fig. 2(a)]. The responsivity of these transitions has a maximum at 148 meV (8.4 μm) and 230 meV (5.4 μm), respectively.

By studying the bias dependence of the interband photocurrent measurements (Fig. 1), the various escape processes from different states in the DWELL structure were clarified. At biases ≤ 2 V, only electrons in the QW excited states (corresponding to peak III, Fig. 1) were able to escape from the QW to contribute to the photocurrent. At biases larger than 2 V, electrons could escape also from the QW ground state (peak II, Fig. 1) as well as from the QD excited state (peak I, Fig. 1). The significant bias dependence of the magnitude of the interband photocurrent peaks was also observed in the intersubband photocurrent measurements, especially for the dominating intersubband transition [peak *i*, Fig. 2(a)]. The bias dependence of the second intersubband photocurrent peak [peak *ii*, Fig. 2(a)] is more moderate, indicating that a different escape mechanism is involved. There are mainly two escape mechanisms, which are influenced by an increased electric field (F) the thermal emission (TE) from the different energy states will be increased by a factor [Eq. (1)] due to a lowering of the potential barrier (Poole-Frenkel effect)^{12–14} and the probability for tunneling through the triangular barrier will increase with the decreasing barrier width [proportional to Eq. (2)],¹⁵ where L_{QW} is the width of the QW, k is Boltzmann's constant, T is the absolute temperature, m is the electron effective mass, ΔE is the barrier

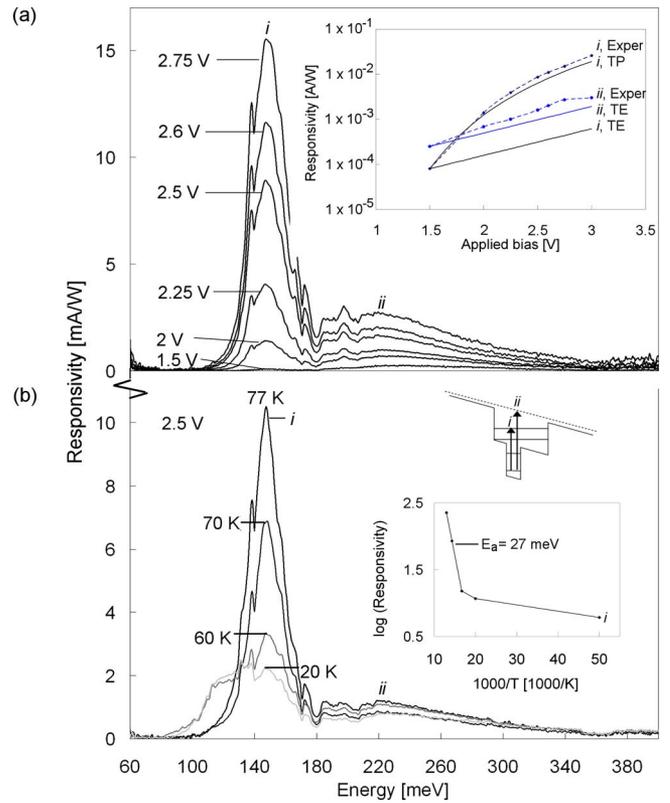


FIG. 2. (Color online) Responsivity measurements showing (a) the bias dependence at 77 K for biases in the range between 1.5 and 2.75 V. Peaks *i* and *ii* correspond to intersubband transitions between the QD ground state and a QW excited state and between the QD ground state and the GaAs barrier, respectively, as labelled in the upper inset in (b). In the inset in (a), the bias dependencies of the responsivity peaks (*i* and *ii*, experimental) are plotted as well as the theoretically predicted increase in the response due to the bias dependence of the tunneling probability and the TE, respectively. (b) The temperature dependence in a range between 20 and 77 K at an applied bias of 2.5 V. In the inset, the logarithm of the responsivity for peak *i* is shown in an Arrhenius plot, from which the activation energy has been deduced to 27 meV.

height, and \hbar is Planck's constant divided by 2π :

$$\exp\left(\frac{eFL_{\text{QW}}}{2kT}\right), \quad (1)$$

$$\exp\left(-4/3 \sqrt{\frac{2m}{\hbar^2}} \frac{\Delta E^{3/2}}{eF}\right). \quad (2)$$

Using the proposed energy level structure (inset, Fig. 1), the experimental bias dependence of the responsivity is compared to the expected increase due to tunneling and TE, respectively [inset, Fig. 2(a)]. From this comparison it can be seen that for the dominating photocurrent peak [peak *i*, Fig. 2(a)], the theoretical bias dependence of the TE is much smaller than the experimentally observed increase in the intersubband photocurrent measurements. However, a good correlation was found with the increased escape rate due to tunneling from the energetically deep lying states in the QW, indicating that this is the dominant escape mechanism. The bias dependence of the second photocurrent peak [peak *ii*, Fig. 2(a)] follows the theoretical bias dependence of the TE.

In order to investigate the role of thermal assistance in the escape processes of the electrons excited to the QW, the temperature dependence of the responsivity was studied [Fig. 2(b)]. The escape routes, which will be influenced by

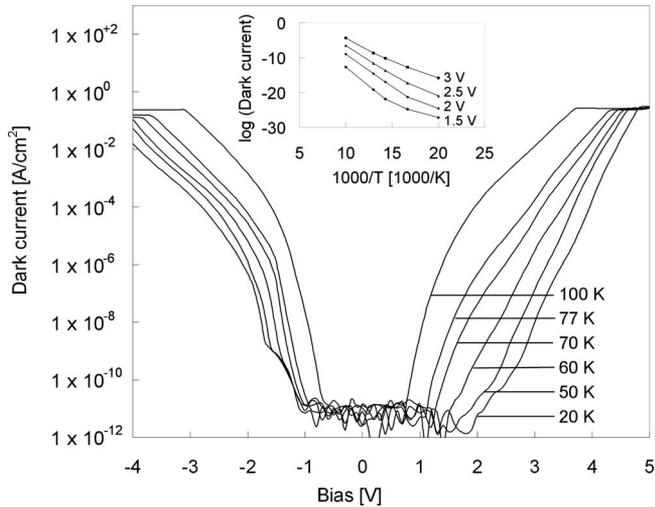


FIG. 3. Dark current in a DWELL IP for temperatures ranging from 20 to 100 K at different applied biases. From the Arrhenius plots in the inset, the activation energies are deduced to 160, 136, 125, and 100 meV at 1.5, 2, 2.5, and 3 V, respectively.

temperature, are the TE to the conduction band and the thermally assisted tunneling.¹⁴ The emission rate associated with thermal excitation is proportional to $e^{-E_a/kT}$, where E_a is the activation energy.¹⁶ When decreasing the temperature successively from 77 to 20 K, the responsivity decreased significantly [Fig. 2(b)]. At temperatures below 60 K the decrease in the responsivity flattens out, indicating a decreased influence of the thermal assistance at lower temperatures. The corresponding activation energy extracted from the Arrhenius plot [inset, Fig. 2(b)] is lower than the proposed energy barrier from the QW excited state to the GaAs conduction band (inset, Fig. 1), which can be due to the high electric field present in the structure.

The bias and temperature dependencies of the dark current in DWELL IPs were also studied (Fig. 3). At low applied biases, the dark current levels were very low at all temperatures, but at higher biases, a rapid increase in the dark current was observed. Several escape routes for the dark current electrons are possible since the DWELL structure includes two electron levels in the QDs and two energy bands in the QWs. Consequently, the activation energies deduced from the dark current measurements will be an effective value including all these escape routes.¹⁶ The activation energy decreases from 160 meV at 1.5 V to 136, 125, and 100 meV at 2, 2.5, and 3 V, respectively. The decrease in the activation energy can partly be explained by the Poole-Frenkel effect since the barrier height is lowered by 15 meV as the applied bias is increased from 1.5 to 3 V, and partly by an increased contribution from the thermally assisted tunneling with the increasing electric field. The fact that the activation energies are lower than the peak detection energies of

the photocurrent could be due to the two-step processes, where thermally excited electrons are tunneling out from excited states in the QDs/QWs, as was observed in the interband photocurrent measurements.

In conclusion, a significant bias and temperature dependence of the escape probability from the different energy levels in the DWELL IP device were demonstrated. It was shown that the thermal assistance also plays an important role for the responsivity. In combination with the strong bias dependence of the intersubband photocurrent, these results imply that the escape processes are limiting factors for the responsivity of the detector. Furthermore, a considerable escape probability from lower lying states at large biases was observed, which could be an important source of dark current.

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