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Temperature dependence of current–voltage characteristics of terahertz quantum-well photodetectors

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Abstract

We have performed current–voltage (*I–V*) measurements on a terahertz quantum-well photodetector (QWP) at different temperatures and employed an emission-capture model to simulate the *I–V* curves. A temperature-dependent vertical electron drift mobility has been used to fit the curves from 7 K to 20 K. Photocurrents caused by 300 K background radiation have also been measured at different temperatures and a background-limited infrared performance (blip) temperature of 12 K for this terahertz detector has been determined. The current–temperature (*I–T*) curves derived from the measured dark *I–V* curves indicate that the thermionic emission process is the major mechanism for dark current in this terahertz detector.

1. Introduction

In recent years, terahertz (1–10 THz) technology has attracted much attention for both fundamental science and application [1]. Along with the remarkable development of terahertz quantum cascade lasers (QCLs) [2–6], the wavelength of peak response of quantum-well infrared photodetectors [7] has been extended into the terahertz region. Advances [8–10] have been made in the optimization of terahertz quantum-well photodetectors (QWPs) after the initial demonstration [11, 12]. The temperature-dependent current–voltage (*I–V*) properties are important characteristics of the terahertz QWPs, especially the dark current and the background limited infrared performance (blip) temperature [13]. The vertical transport of excited carriers has a direct influence on the performance of infrared detectors [14]. These excited carriers experience various scattering events due to optical phonons, electron–electron interaction, impurities [15] and the well barrier interfaces [16] when they are flowing through the multi quantum-well structures. Vertical transport in GaAs/AlGaAs barrier structures has been studied by measuring the vertical current as a function of temperature at different bias voltages [17]. In this paper, we studied the temperature-dependent *I–V* performance of a terahertz QWP and obtained the current–temperature (*I–T*) relationship from the measured dark currents. An emission-capture model was used to simulate the dark current at different temperatures. The simulated *I–V* curves are in agreement with the experimental results. Furthermore, we measured the *I–V* curves at different temperature under the 300 K background condition and acquired the blip temperature of the detector.

2. Dark current simulating model

The current of the device under dark condition is an important parameter. Thermionic emission, direct tunneling and scattering-assisted processes are three main mechanisms of the dark current for a typical quantum-well photodetector. For terahertz QWPs, the first and the third are the dominant ones due to their thick barriers, low applied fields and low operation temperature. According to the emission-capture model and 3D carrier drift model, the dark current is given by [13]

$$J_{\text{dark}} = \frac{em^*}{\pi\hbar^2 L_p}\upsilon(F)\left(\frac{\tau_c}{\tau_{\text{scatt}}}\right)\int_{E_1}^{\infty} T(E,F) \times \left[1+\exp\left(\frac{E-E_f}{k_B T}\right)\right]^{-1} \mathrm{d}E. \quad (1)$$

In this expression, L_p is the period length of the multiple quantum-well structure and equals the sum of quantum well and barrier widths ($L_p = L_w + L_b$), m^* is the effective mass of electrons in GaAs wells, k_B is the Boltzmann constant and $\upsilon(F)$ is the electron drift velocity and takes the usual form

$$\upsilon(F,T) = \frac{\mu(T)F}{\sqrt{1+[\mu(T)F/\upsilon_{\text{sat}}]^2}}, \quad (2)$$

where F is the average field through the active region of the terahertz QWP. υ_{sat} is the saturated drift velocity. In this equation, since the vertical electron drift mobility in the multi quantum-well structure [18] relates to the device temperature, we take the low field mobility $\mu(T)$ as a function of temperature. τ_c is the capture time for an excited electron back into the well and τ_{scatt} is the scattering time to transfer the electrons (with energy greater than the barrier height) on the ground state from the 2D subband to the continuum state on the top of the barrier. The ratio $\tau_c/\tau_{\text{scatt}}$ can be written as [13]

$$\frac{\tau_c}{\tau_{\text{scatt}}} \approx \frac{m_b}{m^*}L_p\left(\frac{m_b k_B T}{2\pi\hbar^2}\right)^{1/2}, \quad (3)$$

where m_b is the effective mass of electrons above the AlGaAs barriers. The temperature-dependent Fermi level in the quantum well has the expression as [19]

$$E_f(T) = k_B T \ln\left[\exp\left(\frac{\pi\hbar^2 L_w N_D}{m^* k_B T}\right)-1\right], \quad (4)$$

where N_D is 3D doping density in the GaAs wells. $T(E,F)$ is the tunneling transmission probability and can be approximated through the WKB approximation as [13, 20]

$$T(E,F) = 1, \qquad \text{for} \quad E \geqslant E_b, \quad (5)$$

$$T(E,F) = \exp\left[\left(-\frac{4}{3eF}\right)\left(\frac{2m_b}{\hbar^2}\right)^{1/2}(E_b-E)^{3/2}\right] \quad \text{for} \quad E_b - eFL_b \leqslant E < E_b \quad (6)$$

$$T(E,F) = \exp\left\{\left(-\frac{4}{3eF}\right)\left(\frac{2m_b}{\hbar^2}\right)^{1/2} \times [(E_b-E)^{3/2}-(E_b-E-eFL_b)^{3/2}]\right\} \quad \text{for} \quad E < E_b - eFL_b. \quad (7)$$

3. Results and discussions

The material of our test device is GaAs/AlGaAs, which was grown by the molecular beam epitaxy (MBE) method. The device consists of 23 modules made of 22.1 nm GaAs wells and 95.1 nm $Al_{0.015}Ga_{0.985}As$ barriers. The center 10 nm region of the 22.1 nm well was doped with Si to 3×10^{16} cm^{-3}. The GaAs/AlGaAs MQWs are sandwiched between 800 nm bottom and 400 nm top GaAs contact layers doped with Si to 10^{17} cm^{-3}. Such a contact doping value was chosen to reduce the contact layer free-carrier absorption and plasma reflection in the terahertz region. In this device structure, we used a wide barrier (95.1 nm) to reduce the tunneling current [9]. Mesa devices with two sizes were fabricated using standard GaAs processing techniques. Device characteristics were performed in a temperature-controlled helium cryostat.

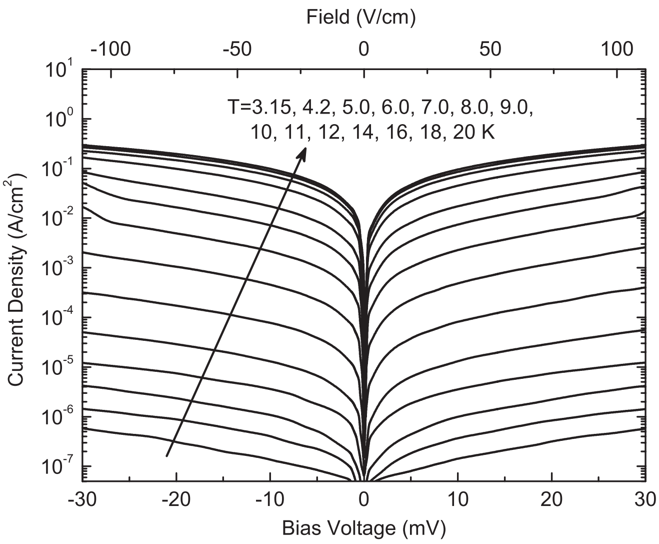

Figure 1. Measured current–voltage (*I*–*V*) curves under dark condition from 3.15 K to 20 K.

The operation voltages of this terahertz QWP are from several millivolts to thirty millivolts. Scattering-assisted escape of the electron is the dominant process at low fields for a typical quantum well photodetector [13]. The measured *I*–*V* curves under dark condition are shown in figure 1. The bottom-out behavior due to the remaining inter-well tunneling or other mechanisms [13] has not been observed. It is because that the thermionic emission and field-assisted tunneling are much stronger than inter-well tunneling for thick barrier structures within the temperature range from 3.15 K to 20 K. We used equation (1) and a temperature-dependent mobility ($\mu(T)$) to simulate the above *I*–*V* curves with a voltage range from 0.1 mV to 30 mV and a temperature range from 7 K to 20 K. As shown in figure 2, the theoretical results (*solid lines*) agree well with the experimental measurements (*spheres*), which proves that the emission-capture model is well suited for describing the dark current of terahertz QWPs under low field and low temperature conditions.

The blip temperature (T_{blip}) is defined as the temperature at which the detector operating under the condition that the photocurrent caused by the 300 K background radiation (J_{backgr}) equals the dark current (J_{dark}). For operations at and lower than T_{blip}, the detector is said to be under blip condition. Experimentally, the T_{blip} of terahertz QWPs can be derived from comparing the dark current curves with the photocurrent

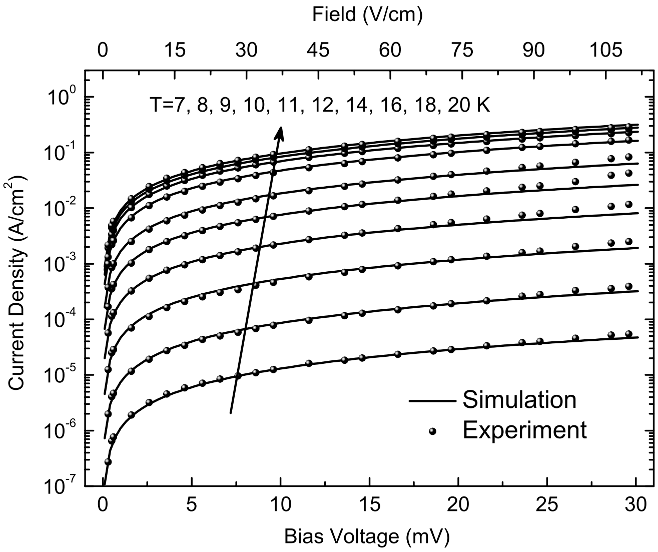

Figure 2. Comparison between theoretical results (*solid lines*) and experimental measurements (*spheres*) about the *I–V* curves from 7 K to 20 K.

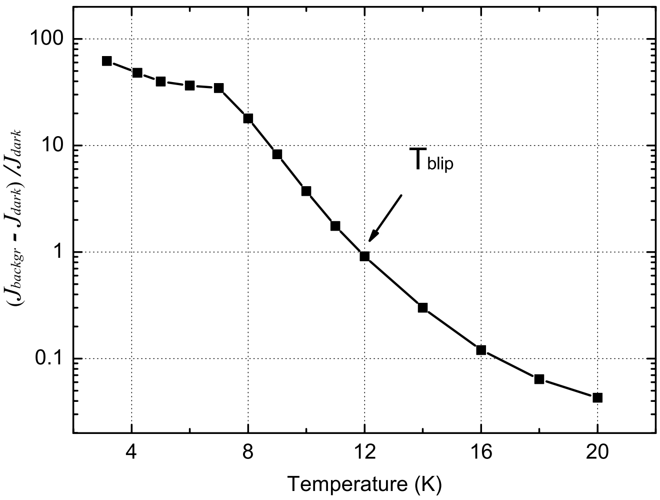

Figure 3. Variation of the ratio $(J_{\mathrm{backgr}} - J_{\mathrm{dark}})/J_{\mathrm{dark}}$ as a function of the device temperature. Here, J_{backgr} includes the dark current. A blip temperature of 12 K for this detector can be obtained from the curve.

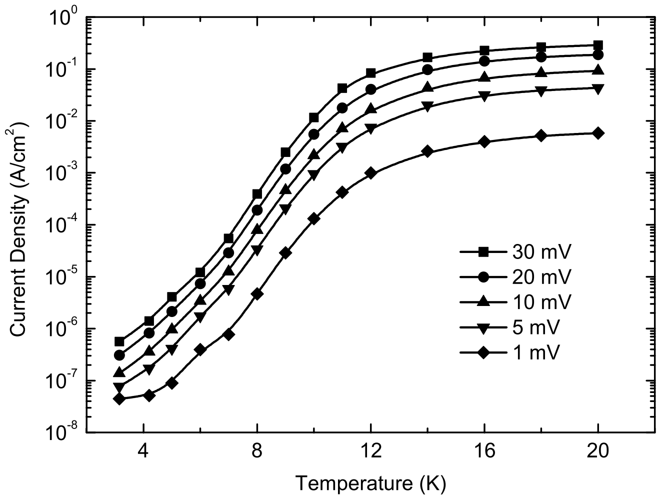

Figure 4. Current–temperature (*I–T*) characteristic measured at selected bias voltages.

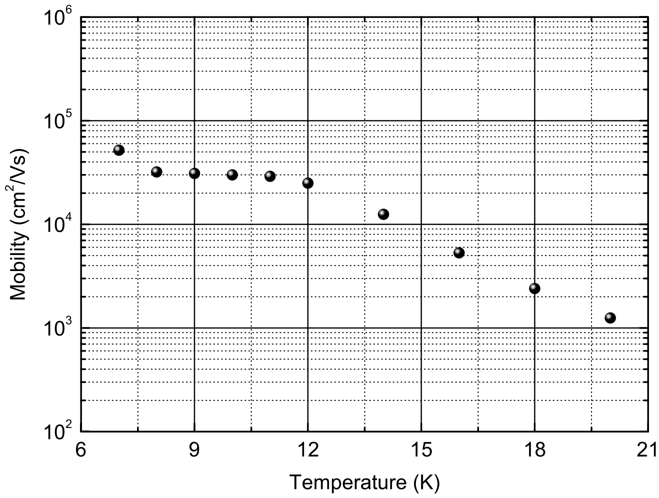

Figure 5. Vertical electron drift mobilities in the device structure fitted by equation (1) versus device temperatures.

curves obtained by allowing the 300 K background radiation through the Dewar window. The photocurrents of the detector under the 300 K background condition were measured at different temperatures and then we plot the temperature-dependent ratio $(J_{\mathrm{backgr}} - J_{\mathrm{dark}})/J_{\mathrm{dark}}$ in figure 3. Here, J_{backgr} includes the dark current. A T_{blip} of 12 K for this terahertz detector is seen in the curve. The approximately exponential decreasing of this ratio curve indicates that the detector performance decreases dramatically with temperature.

Sequential tunneling and thermionic emission are two major dark current mechanisms in GaAs/AlGaAs barrier structures [19] and the latter becomes dominant for thick barrier structures. The *I–T* curves have been obtained from the measured dark currents and shown in figure 4. The dark current decreased by about 6–7 orders of magnitude in accordance with the thermally activated character of the thermionic emission [17, 21] when the device was cooled from 20 K down to 3.15 K. This result indicates that the use of the emission-capture model, combined with the 3D carrier drift model, is reasonable while describing the dark current of this detector. A steep drop of the *I–T* curves when the device temperature $\leqslant$12 K has been observed, which is consistent with the good performance when the device operating at and lower than T_{blip}.

In the simulating process for the dark currents, it is important to note that a temperature-dependent mobility parameter was employed to fit the amplitude of the *I–V* curves. The employed mobilities are shown in figure 5 and have a decrease trend with the device temperature. This is an inverse trend in contrast with the Hall mobility which is of an ionized impurity scattering origin [22] in the relatively pure GaAs materials at the temperature below 20 K. This reason may be related to the fact that we have neglected the nonuniformity of the electric field in the device and other mechanisms like hopping conduction in our model under the above temperature range, and the details need further study.

4. Conclusion

In conclusion, the *I–V* characteristics for a terahertz QWP have been measured at different temperatures. An emission-capture model combined with the 3D carrier drift model and a temperature-dependent vertical electron drift mobility have been employed to simulate the dark current of the detector. The simulated results agree very well with the experimental measurements, which proves that the emission-capture model is a good description for the dark current of the terahertz QWPs under low field and low temperature conditions. The reason for the decrease of the fitted mobility with the temperature needs further study. Photocurrents due to the 300 K background radiation have also been measured. The $(J_{\mathrm{backgr}} - J_{\mathrm{dark}})/J_{\mathrm{dark}}$ ratio curve shows a dramatic decline of the detector performance with temperature and a 12 K blip temperature has been determined from the curve. Finally, the *I–T* characteristics have been obtained from the measured dark currents and indicate a dominant thermionic emission origin of dark current due to the thick barriers and low temperature.

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