Comparison Studies of Infrared Phototransistors with a Quantum-Well and a Quantum-Wire Base

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Abstract. Infrared phototransistors based respectively on a quantum-well and a quantum-wire structures, utilizing intersubband electron transitions, are considered using developed analytical model. The dark currents and responsivities of the phototransistors in question are compared. It is shown that the quantum-wire infrared phototransistor can surpass the infrared phototransistor with a quantum well in performance especially at low temperatures. This is due to the one-dimensional nature of the electrons in the quantum-wires providing higher energy of thermal excitation, leading to low dark current and sensitivity to normal incident radiation.

1. INTRODUCTION

Quantum-well (QW) structures are widely used in the phototransistors as elements sensitive to infrared radiation (see Ref. [1]) due to intersubband electron transitions. The QW structure plays a role of the phototransistor base. The theory of the quantum-well infrared phototransistors (QWIPs) based on a single-QW structure has been developed previously [2-5]. It has been shown that the properties of the QW base of the QWIP significantly affect the performance of the latter.

In this paper we compare the QWIP with a novel infrared phototransistor – the quantum-wire infrared phototransistor (QRIP). In contrast with the QWIPs the base of the proposed QRIP consists of an array of QRs (for the sake of distinction we use the following notations: quantum well - QW and quantum wire - QR). These QRs are formed by narrow-gap material ($n-$type doped or undoped) regions buried in an undoped wide-gap material sandwiched between the doped contact layers. The QWIP and QRIP structures are schematically shown in Fig. 1. The QR base of the QRIP provides the sensitivity to normal-incident infrared radiation and reduction of the dark current. Both effects are due to additional lateral confinement of the electrons in the QR (in comparison to the QW) which, in turn, leads to the possibility of the photoexcitation of the electrons by normal-incident radiation and lowering of the Fermi energy of the electrons in the QRs.

2. CURRENT DENSITY

Let us consider the QWIP and QRIP with the structures of Fig. 1. We suppose that the QWs and QRs forming the base of the QWIP and QRIP have a single quantum level. Therefore the electrons in a QW form the two-dimensional electron gas while in a QR they form the one-dimensional gas.

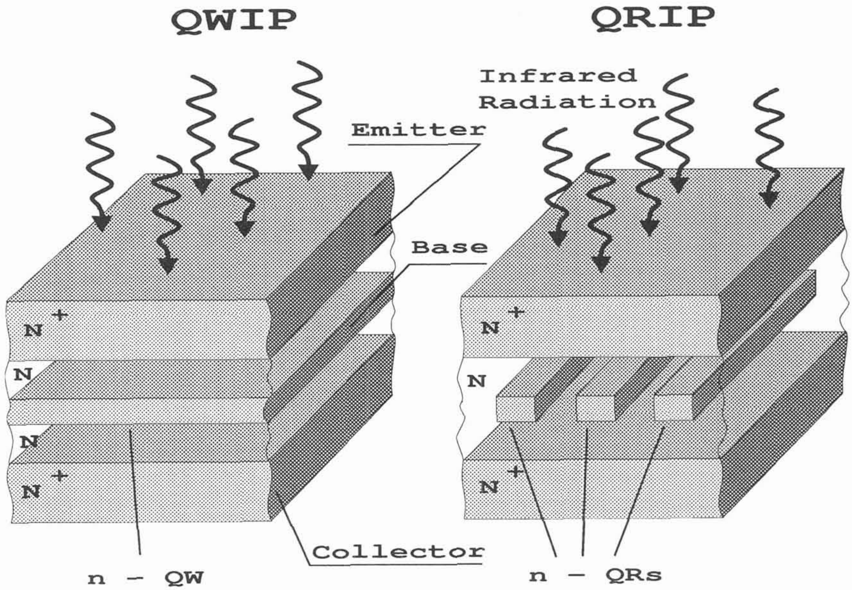

Figure 1: Schematic view of the QWIP and QRIP structures.

By analogy with our previous consideration [4,5], supposing that the electrons escape from the QW and QRs only due to the thermionic emission or photoemission, one can obtain the following common expression for the current density in the QWIP and QRIP averaged over their base planes:

$$j = \left(\frac{1+\beta}{1-\beta}\right)\left[\frac{1-\exp(-e\,V/k\,T)}{1+\exp(-e\,V/k\,T)}\right]\left[j_T < \exp\left(\frac{e\,\delta\varphi}{k\,T}\right) > + \frac{1}{2}\,e\,\sigma\ < \Sigma > I\right] \tag{1}$$

Here β is the efficiency of the electron transport through the QR base (so that $\alpha = 1-\beta$ is the probability of the capture of the injected electrons in the QR base), e is the electron charge, V is the voltage applied between the collector and emitter, k is the Boltzmann constant, T is the temperature, σ is the cross-section of the photoescape of the electrons from the quantum level due to absorption of the photon, $< \Sigma >$ is the average sheet density of the electrons in the base, I is the intensity of the incident infrared radiation, j_T is the density of the thermionic current from the base to the collector (or emitter), $\delta\varphi = \varphi - < \varphi >$, φ is the potential in the QR base plane. Symbol $< ... >$ means averaging over the base plane.

Despite the common form of the expression for the current density the terms in expression (1) can be quantitatively and qualitatively different for the QWIP and QRIP. First of all, the probability of the electron capture into the QR base and, consequently, the current gain $g = (1+\beta)/(1-\beta)$ can significantly differ from those in the QWIP. It is very important that in the case of the QR base the photoescape cross-section σ has different polarization dependence, providing the sensitivity of the QRIP to normal-incident radiation. Finally, the thermionic current j_T from the QR base, which determines the dark current value, also has different dependence on the average electron sheet density Σ.

In the case of degenerate one-dimensional electron gas in the QRs under large bias voltages ($e\,V >> k\,T$) we have the following formulae for the dark current density j_{dark} and the photocurrent density Δj:

$$j_{dark} = \left(\frac{1+\beta}{1-\beta}\right) j_T\, \theta \sim \left(\frac{1+\beta}{1-\beta}\right) \cdot \theta \cdot \exp\left(-\frac{\varepsilon_i}{kT}\right) \cdot \exp\left[\frac{(\pi\, \hbar\, a\; < \Sigma >)^2}{8\, m\, k\, T}\right], \tag{2}$$

and

$$\Delta j = \frac{1}{2}\left(\frac{1+\beta}{1-\beta}\right) e\, \sigma < \Sigma > I, \tag{3}$$

$\hbar$ is the Planck constant, ε_i is the ionization energy of the quantum level in the QW and QR, m is the effective electron mass, a is the spacing between QRs in the QRIP base. Evaluating the average electron sheet density for the undoped QR base one can obtain (compare with the related formulae from Refs. [4,5]):

$$< \Sigma > \approx \Sigma_i + \frac{æ\, V}{4\, \pi\, e\, W_c}, \qquad \Sigma_i = \frac{æ}{4\, \pi\, e^2}\left(\frac{W_e + W_c}{W_e\, W_c}\right)(\varepsilon_i + \varepsilon_F) \tag{4}$$

Here æ is the lattice permittivity, W_e and W_c are the thicknesses of the emitter and collector N regions (see Fig. 1), and ε_F is the Fermi energy of the electrons in the emitter and collector regions.

For the QWIP with a uniform QW $\varphi =< \varphi >$ and the parameter of nonuniformity $\theta = < \exp\left(\frac{e\, \delta\, \varphi}{k\, T}\right) >= 1$.

To calculate the parameter of nonuniformity θ for the QRIP we solve the Poisson equation for the potential variation $\delta\varphi$ supposing that the sheet electron density in the QR base is a periodic function due to the periodicity of the QR array. We set $\varphi = 0$ and $\varphi = V$ at the emitter and collector planes. As a result we obtain the following expression for the parameter of nonuniformity of the QRIP:

$$\theta = \prod_{n=1}^{\infty} I_0\left(\frac{2\, e^2\, a < \Sigma > \Delta_n}{æ\, k\, T\, n\, K_n}\right) \tag{5}$$

Here $I_0(x)$ is a Bessel function of imaginary argument,

$$K_n = \coth\left(\frac{2\, \pi\, n\, W_e}{a}\right) + \coth\left(\frac{2\, \pi\, n\, W_c}{a}\right),$$

and Δ_n is the amplitude of the n-th harmonic in the sheet electron density distribution. In the case under consideration one may set $\Delta_1 \approx 1$ and $\Delta_2, \Delta_3, ... \ll 1$. It means that in product (14) the factors with $n > 1$ are close to unity. If $a \leq W_e, W_c$ we have $K_n \approx 2$ and formula (5) yields

$$\theta \approx I_0\left(\frac{e^2\, a < \Sigma >}{æ\, k\, T}\right) \tag{6}$$

The dependences of the photocurrent-to-dark current ratio S versus the average sheet electron density $< \Sigma >$ and applied voltage V for the QRIPs with various spacings between the QRs at $T = 50$ K are shown in Figs. 2, 3. We set $m = 6 \times 10^{-29}$ g, æ $= 12$ supposing the QRs made of GaAs. It is seen that the photocurrent-to-dark current ratio as a function of the average electron sheet density has a maximum. The value of this maximum and corresponding optimum value of the average electron sheet density depend noticeably on the spacing a.

3. COMPARISON OF THE QRIP AND QWIP DARK CURRENTS AND RESPONSIVITIES

Using formulae (1)-(6) one can obtain the following relationship for the ratios of the dark currents and responsivities for the QRIP and QWIP with the same average sheet electron density:

$$\frac{j_{dark}^{QR}}{j_{dark}^{QW}} \approx \left(\frac{1-\beta^{QW}}{1-\beta^{QR}}\right) \cdot \exp\left[\frac{(\pi \hbar a < \Sigma >)^2 - 8\pi\hbar^2 < \Sigma >}{8 m k T}\right] \cdot I_0\left(\frac{e^2 a < \Sigma >}{æ k T}\right), \quad (7)$$

$$\frac{R^{QR}}{R^{QW}} \approx \left(\frac{1-\beta^{QW}}{1-\beta^{QR}}\right) \cdot \frac{\sigma^{QR}}{\sigma^{QW}}. \quad (8)$$

Here we suppose that $(1-\beta^{QR}), (1-\beta^{QW}) \ll 1$. The ratio of the dark current densities versus average electron sheet density according to formula (7) is shown in Fig. 4. Taking into account formula (4) this ratio as a function of the applied voltage can be presented as it is seen in Fig. 5. The value of the dark currents ratio $j_{dark}^{QW}/j_{dark}^{Qr}$ is determined by two competitive effects: (1) lowering of the Fermi energy of the electrons in the QRs (in comparison with the QWs) due to high density of states in the one-dimensional electron gas, and (2) the increase of the current density in the regions between the QRs owing to the potential sag in these regions.
The effect of reduction of the thermionic emission from the QRs attributed to lower Fermi level becomes more significant with decreasing temperature than the effect of the potential barrier sag (Figs. 4, 5). Thus despite the increase of the dark current density in the space between the QRs due to the sag of the potential barrier the total dark current in the QRIPs can be significantly lower than that in the QWIPs. The ratio of responsivities R^{QR}/R^{QW} can be different depending on the probabilities of the electron capture β^{QR} and β^{QW} and the photoescape cross-section. In the case of normal incident radiation R^{QR}/R^{QW} can be definitly much more than unity. Therefore the useful effects connected with the implementation of the QR base structure (low rate of the thermionic emission from the QRs and sensitivity to normal-incident radiation) override the harmful effect of the current leakage between the QRs and result in some advantages of the QRIPs in comparison with the QWIPs.

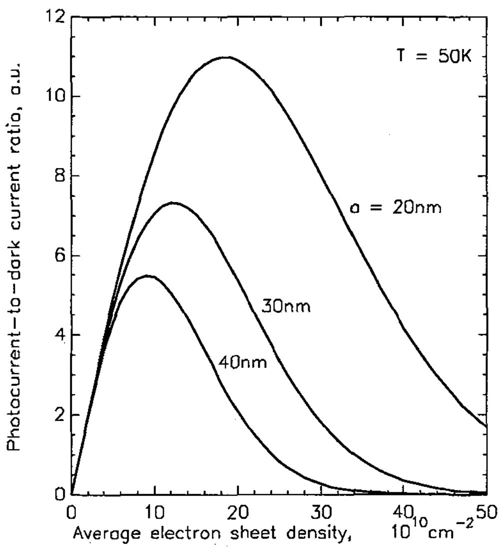

Figure 2: Photocurrent-to dark current ratio S versus the average electron sheet density $< \Sigma >$.

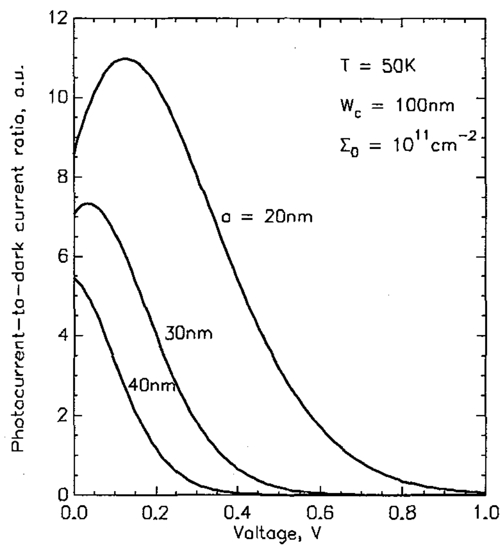

Figure 3: Photocurrent-to dark current ratio S as a function of the applied voltage V.

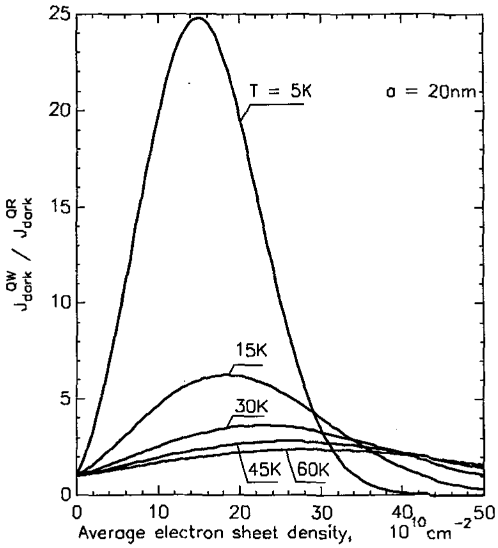

Figure 4: Ratio of the dark currents as a function of the average electron sheet density $< \Sigma >$.

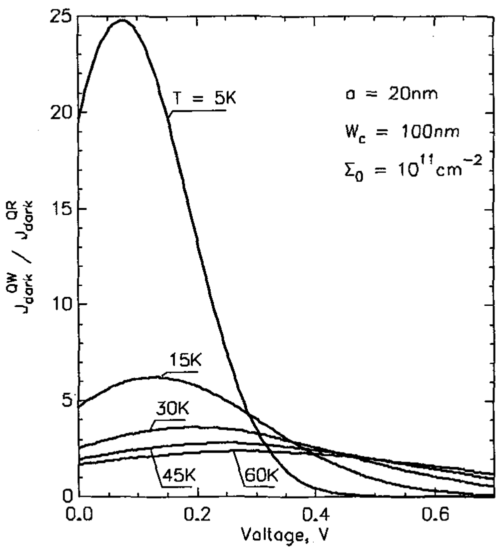

Figure 5: Ratio of dark currents versus applied voltage V.

4. CONCLUSION

It was shown that the utilization of the QR array instead of the QW as a base of intersubband infrared phototransistors provides the enhancement of their performance. This is connected with the transition from the two-dimensional electron gas (in the QW base) to the one-dimensional electron gas (in the QR base).

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