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Optical interference and nonlinearities in quantum-well infrared photodetectors

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Abstract

The effects of optical interference in quantum-well infrared photodetectors (QWIPs) caused by reflection of radiation from the metal contact are investigated. It is shown that interference leads to strong deterioration of QWIP characteristics (responsivity, noise, and noise equivalent power (NEP)) if signal photocurrent is larger than the dark current or background current. This is caused by the nonuniform distribution of the photogeneration rate, electric field, and all other microscopic physical quantities. As a result, the photocurrent gain and photoionization efficiency are decreased, while the noise gain is increased with respect to their values for uniform excitation. Several puzzling experimental effects – a strong increase of the QWIP NEP for high-power heterodyne operation and temperature dependence of QWIP responsivity – can be explained by the model described above. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Quantum-well infrared photodetectors; Nonlinearity; Optical interference; Responsivity

1. Introduction

Photoconductivity of quantum-well infrared photodetectors (QWIPs) is determined by the carrier photogeneration from the QWs and their transport in the QW structure [1]. Conventional QWIP theories assume that the electric field and photogeneration rate are constant across QWIP structure. Therefore, it is commonly believed that QWIP characteristics (responsivity, detectivity, etc.) are independent of temperature and incident infrared power. It has been shown recently [2,3] that QWIPs with *small* number of QWs can display nonlinear photoresponse at relatively high infrared power. The decrease of responsivity occurs due to the voltage drop on the injection barrier and modulation of the electric field in the bulk of QWIP. These phenomena, however, cannot explain several puzzling experimental effects in QWIPs with *large* number of QWs. One of these effects observed recently is an unexpected large value of the QWIP noise equivalent power (NEP) in heterodyne mode of operation [4]. The observed value of the NEP exceeded the value $\mathrm{NEP}(0) = 2\hbar\omega\Delta f/\eta$ (predicted by conventional heterodyne theories [5]) by a factor of 10 (!). Another effect reported recently is temperature dependence of QWIP responsivity [6].

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We believe that these nonlinear effects can be explained by the non-uniform distribution of the infrared radiation intensity (and photoexcitation rate) in QWIPs. The nonuniformity of light distribution due to attenuation in QWIPs and other photodetectors has been studied in Refs. [7–10]. The influence of the radiation interference on detector characteristics has been reported in Refs. [11,12].

The nonuniformity of the light intensity in QWIP caused by the reflection from the metal contact and interference was demonstrated experimentally [13]. If the photoexcitation rate from the QWs exceeds the thermoionization rate, the nonuniformity leads to the modulation of the electric field and other physical quantities in the bulk of QWIP, resulting in deterioration of QWIP characteristics. The present paper reports detailed investigation of these effects.

2. Numerical model

Numerical simulation of QWIP operation was performed using a one-dimensional simulator [14] solving self-consistently equations describing physical processes in QWIP – Poisson equation, current continuity equation in the drift-diffusion approximation, and rate equations for capture and emission in QWs. The physical parameters of the model – field-dependent electron mobility, thermoionization rate from the QWs, and photoexcited electron escape probability – were fitted to the experimental dark current–voltage and responsivity–voltage characteristics, which is necessary to obtain realistic simulation results. The escape probability has been described by a model proposed in Ref. [15]. Calculation of QWIP characteristics has been done as follows. Dark current regime was simulated first, followed by simulation of illuminated conditions corresponding to various levels of incident infrared power. The responsivity was calculated as a difference of the total current at a given infrared power and the dark current, normalized to the power level. The photocurrent gain is given by the ratio of the photocurrent to total QW excitation rate caused by illumination. The photoionization efficiency is calculated as the ratio of the QW photoexcitation rate to incident photon flux. Note that with this definition of gain and efficiency the photoexcied carrier escape probability is included into the photoionization efficiency. The noise has been evaluated according a model proposed in Ref. [16]. The noise power spectral density can be represented in a conventional form $S_I = 4eg_nI$, where I is the total current and g_n is the noise gain given by the expressions:

$$g_n = \frac{\sum_{i=1}^{N} z_i^2(1 - p_i/2)/p_i}{(\sum_{i=1}^{N} z_i)^2}, \qquad (1)$$

where z_i is the impedance of the ith barrier and p_i is the capture probability of the ith QW. Local impedance has been calculated as $z_i = \Delta V_i/\Delta I$, where ΔV_i is the change of the voltage drop across ith barrier to the change of current in QWIP upon application of a small voltage step (5 mV).

The noise equivalent power (NEP) (for heterodyne regime) is given by the expression

$$\mathrm{NEP}(P) = \mathrm{NEP}(0) \times [\eta(0)/\eta(P)] \times (g_p/g_n), \qquad (2)$$

where $\mathrm{NEP}(0) = 2\hbar\omega\Delta f/\eta$ is the low-power NEP value, and $\hbar\omega$ is the photon energy.

Calculations have been performed for GaAs/$Al_{0.26}Ga_{0.74}As$ QWIPs with 32 QWs of 60 Å width, separated by barriers of 232 Å width. The barriers were undoped, and the QWs were center δ-doped with silicon to about 9×10^{11} cm^{-2}. The GaAs contacts were doped at 1.5×10^{18} cm^{-3}. These QWIPs were studied in detail both experimentally and theoretically earlier [2,17,18]. Optical excitation rate was assumed to be proportional to $\cos^2(kx)$, where k is the x-component of the wave vector, and x is the coordinate perpendicular to the QW plane ($x = 0$ corresponds to the metal–semiconductor interface). This distribution corresponds to 45° illumination geometry and perfect reflection from the metal contact [13].

3. Results

Fig. 1 shows the dependence of the responsivity, photocurrent gain, and photoionization efficiency on incident infrared power at temperature $T = 77$ K and applied bias $V = 1$ V. Responsivity is constant at low-power, decreases with power, and saturates at low value for high infrared power. The responsivity is decreased by a factor of 5 at high power. The onset of the responsivity degradation occurs when the photocurrent exceeds the dark current. Responsivity is determined by the product of the photocurrent gain g_p and

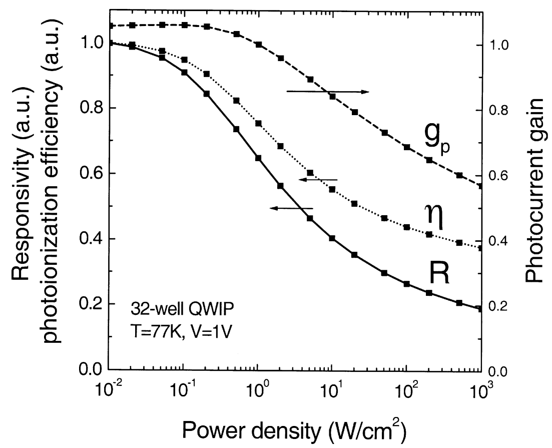

Fig. 1. Photoresponsivity R, photocurrent gain g_p, and photoionization efficiency η versus incident infrared power for 32-well QWIP at temperature $T = 77$ K and applied voltage $V = 1$ V. The dashed-dotted line shows the distribution of optical power.

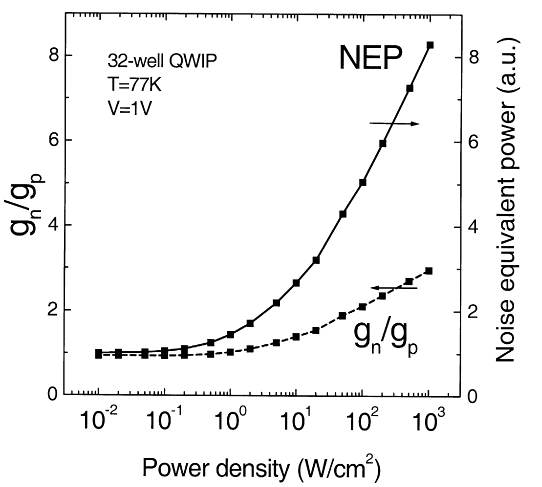

Fig. 2. Power dependence of the noise equivalent power NEP and noise gain-to-photocurrent gain ratio.

photoionization efficiency $\eta : R = eg\eta/(\hbar\omega)$, where e is the electron charge. The decrease of the responsivity is caused by the degradation of both g_p and η, the reasons of which will be clear from the analysis of spatial distributions of physical quantities in QWIP.

Power dependence of the noise gain-to-photocurrent gain ratio and NEP are plotted in Fig. 2. The gain ratio is increased by a factor of 3, while the NEP is

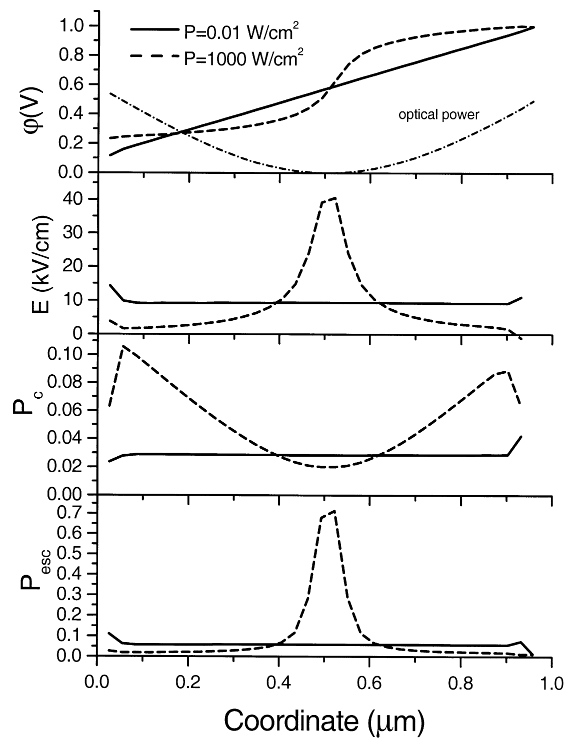

Fig. 3. Coordinate dependence of (a) potential, (b) electric field, (c) QW capture probability, and (d) photoexcited electron escape probability for low-power (solid line) and high-power (dashed line) densities.

enhanced by about an order of magnitude (!) with respect to their low-power values.

Fig. 3 illustrates the distributions of physical quantities in QWIP in the dark regime and under high-power illumination. At low power, the potential is almost linear with coordinate, indicating the uniformity of the electric field and other relevant quantities. However, at high power, the electric field is distributed nonuniformly across QWIP. This is caused by the nonuniform optical generation rate, having a minimum near the center of QWIP structure. To keep the total current constant in each cross-section, the QWs are recharged to provide higher electric field in unilluminated regions. As a result, the electric field in illuminated regions is decreased, causing the lowering of the drift electron velocity, photoexcited carrier escape probability, and increasing the capture probability. In unilluminated region, the increased electric field results in enhancement of the tunneling-assisted

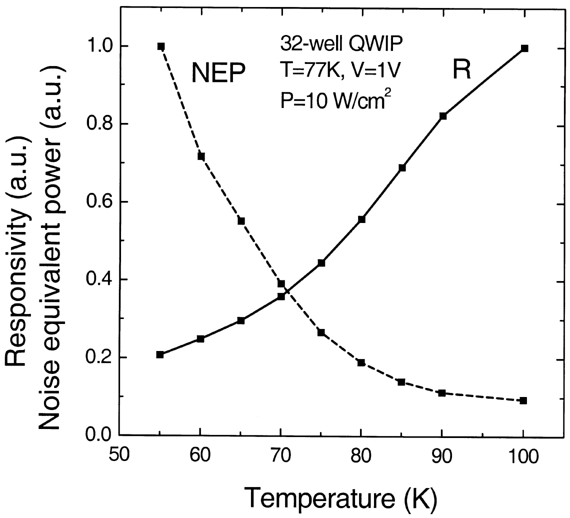

Fig. 4. Temperature dependence of responsivity and noise equivalent power for 32-well QWIP at incident power density of $P = 10\ \mathrm{W/cm^2}$.

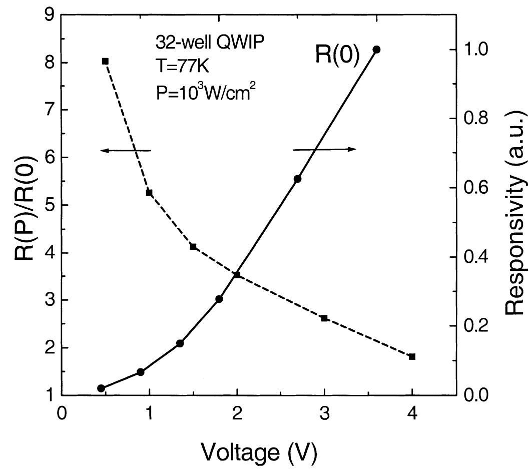

Fig. 5. Low-power responsivity and high-to-low power responsivities ratio for 32-well QWIP at $T = 77$ K.

thermal ionization, which effectively plays the role of the photoexcitation.

The temperature dependence of the responsivity and NEP at incident power density $P = 10\ \mathrm{W/cm^2}$ is plotted in Fig. 4. The effect of the temperature increase on the QWIP characteristics is equivalent to that of the lowering of infrared power – both R and NEP are improved with temperature (compare with Figs. 1 and 2). Thus, the nonlinearity of QWIP characteristics is determined primarily by the ratio of the thermal excitation rate to (nonuniform) optical excitation rate, rather than by particular value of incident infrared power.

Fig. 5 shows the voltage dependence of QWIP responsivity and ratio $R(P)/R(0)$. The voltage increase helps to minimize the ratio $R(P)/R(0)$, i.e. to suppress the nonlinear effects. This is due to a strong enhancement of thermal excitation rate with applied voltage.

4. Conclusions

We have shown that optical interference effect can lead to strong nonlinearities of the QWIP characteristics. Responsivity, NEP, and gain ratio are deteriorated when the nonuniform optical excitation rate exceeds the thermal ionization or background excitation rates. These effects are caused by the nonuniform electric field distribution. They can play an important role for heterodyne (or other high-power) operation, and for low-temperature/low-background applications.

Acknowledgements

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