Towards a voltage tunable two-color quantum-well infrared photodetector

Amlan Majumdar[a)]
Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

K. K. Choi
U.S. Army Research Laboratory, Adelphi, Maryland 20783

L. P. Rokhinson and D. C. Tsui
Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

(Received 24 July 2001; accepted for publication 16 November 2001)

Two-color quantum-well infrared photodetectors (QWIPs), based on electron transfer between coupled QWs, suffer from the presence of the shorter wavelength peak at all bias voltages V_b. We investigate this problem by studying the bias dependence of absorption coefficient α and photoconductive gain g as a function of wavelength at 10 K. We fabricate such a detector with a peak wavelength of 8 μm for both bias polarities but a voltage tunable cutoff wavelength (9 μm for $V_b > 0$ and 11 μm for $V_b < 0$). We use corrugated QWIPs with different corrugation periods to extract α and g for different values of V_b. We find $\alpha \approx 0.1\ \mu\text{m}^{-1}$ in the 6–12 μm range with small peaks at 8 and 9.8 μm for $V_b > 0$ and 10 μm for $V_b < 0$. g has a pronounced peak at 7.8 μm for both bias polarities and determines the line shape of the QWIP spectral responsivity. These results are attributed to insufficient electron transfer between the coupled QWs and to low tunneling probability of the longer wavelength photoelectrons. A modified QWIP structure has been proposed for complete switching of spectral responsivity peak when the bias voltage polarity is reversed. [DOI: 10.1063/1.1436529]

Multicolor infrared detection is an area of active research because it can be used for remote temperature sensing.[1,2] Quantum-well infrared photodetectors (QWIPs) are suitable for multicolor detection because their absorption wavelength can be tailored by varying device and material parameters and their intrinsic absorption line shape is narrow. QWIPs with two stacks of QWs, each designed to detect a different wavelength, are the simplest two-color detectors.[3] Focal plane arrays using two stacks of QWs have been recently fabricated.[4] Two-color QWIPs with one stack of QWs, where detection wavelength can be changed with bias voltage, have certain advantages over two-stack QWIPs such as simpler readout circuits for focal plane arrays.

Voltage tunable two-color detectors have been proposed in the past based on two main physical mechanisms. The first approach is to change the energy level structure and wave functions of excited states under bias by using asymmetric coupled QWs,[5] graded barriers,[6] or asymmetric step wells.[7] The second approach is based on electron transfer between ground states of adjacent QWs under a voltage bias. This process was first observed in multiple QW (MQW) structures that had alternately doped QWs[8] and later used to achieve voltage tunable two-color detection.[9] In this approach, voltage switching is less effective for longer wavelength detection because of the persistence of the shorter wavelength peak.

In this letter, we investigate the presence of the shorter wavelength peak in these two-color QWIPs for all bias voltages. We fabricate a QWIP with a responsivity peak at 8 μm for all voltages V_b and a voltage tunable cutoff wavelength (9 μm for $V_b > 0$ and 11 μm for $V_b < 0$). We study the V_b dependence of absorption coefficient α and photoconductive gain g that are extracted using corrugated-QWIPs (C-QWIPs) with different corrugation periods.[10–12] We find that α is almost constant in the 6–12 μm range with small peaks at 8 and 9.8 μm for $V_b > 0$ and at 10 μm for $V_b < 0$, and that g has a pronounced peak at 7.8 μm for both polarities of V_b. Based on these results, we conclude that there is insufficient electron transfer between the coupled QWs and that the tunneling probability of the longer wavelength photoelectrons is low.

The two-color QWIP consists of 36 periods of coupled QWs sandwiched between a 0.5 μm thick n^+-GaAs top contact layer (1×10^{18} cm^{-3} Si doping) and a 1.5 μm thick n^+-GaAs bottom contact layer (5×10^{17} cm^{-3} Si doping). Each period consists of a 40 Å GaAs well coupled to a 44 Å GaAs well through a 50 Å $Al_{0.28}Ga_{0.72}As$ barrier and separated from the next set of coupled wells by a 200 Å $Al_{0.28}Ga_{0.72}As$/300 Å $Al_{0.22}Ga_{0.78}As$ barrier. All the QWs are uniformly doped (5×10^{17} cm^{-3} Si doping) and the barriers undoped. We calculated the energy levels in the MQW structure using the transfer matrix method.[1] At zero bias, the 40 Å wide left QW has two bound states separated by 116 meV ($\lambda = 10.7\ \mu$m) while the 44 Å wide right QW has a bound state and an extended state with an energy difference of 151 meV ($\lambda = 8.2\ \mu$m). We apply V_b to the top contact while keeping the bottom one grounded. The conduction band diagram of this photodetector is shown in the inset of Fig. 1. For positive bias, electrons tunnel from the ground state of the left QW to the ground state of the right QW. When infrared radiation is coupled into this detector, electrons are photoexcited from the ground state to the extended state of the right QW. These photoelectrons are swept away by electric field to

[a)]Electronic mail: majumdar@ee.princeton.edu

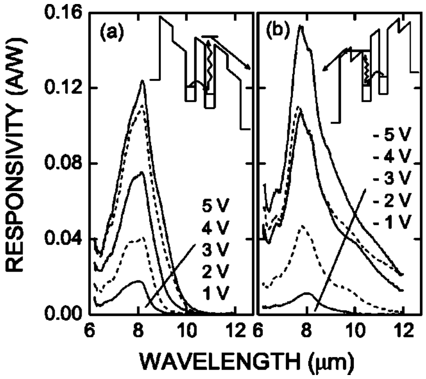

FIG. 1. Spectral responsivity R of 45°-edge coupling QWIP measured at 10 K for (a) positive and (b) negative bias V_b. For both (a) and (b), $|V_b|=1$, 2, 3, 4, and 5 V for the bottom to the top curve. Inset: Conduction band diagram and photoexcitation mechanism of two-color QWIP based on coupled QWs for (a) positive and (b) negative V_b.

form a photocurrent. Thus, we expect to detect 8.2 μm radiation for $V_b>0$. For negative bias, electron transfer from the right QW to the left QW should lead to the detection of 10.7 μm radiation. It is important to note that for $V_b<0$, these long wavelength photoelectrons have to tunnel through a barrier before contributing to photocurrent.

We processed 45°-edge coupling QWIPs using photolithography and wet etching. These devices have an area of $200\times200\ \mu m^2$. Au/Ge/Au contacts were evaporated and alloyed in a rapid thermal annealer to form ohmic contacts to the top and bottom n^+-GaAs layers. ac photoresponse measurements were performed at 10 K in the wavelength range from 6 to 12 μm. We show the responsivity R spectra in Fig. 1. The QWIP detects 8 μm radiation for both positive and negative V_b. Although there is no peak in responsivity around 10.7 μm for $V_b<0$, there is significant photoresponse between 10 and 12 μm. Thus, this detector has a voltage tunable cutoff wavelength while the peak detection wavelength is fixed at 8 μm. We define cutoff wavelength as $\lambda=\lambda_c$ where R drops to 20% of its peak value $[R(\lambda_c)=0.2\times R(\lambda_p)$, where λ_p is the peak wavelength]. λ_c, plotted in Fig. 2(a), is 9 μm for $V_b>0$ and 11 μm for $V_b<0$. This figure demonstrates the voltage tunability of λ_c of the QWIP. Figure 2(b) shows the bias dependence of electron activation

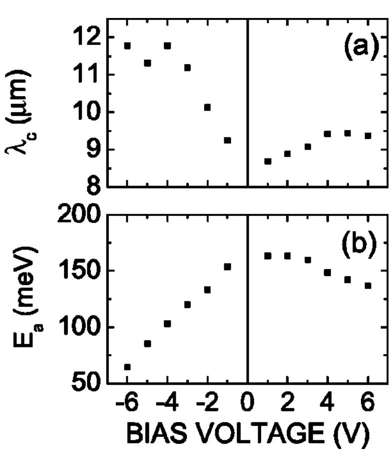

FIG. 2. Bias V_b dependence of (a) cutoff wavelength λ_c and (b) electron activation energy E_a of two-color QWIP. λ_c is obtained from Fig. 1 using $R(\lambda_c)=0.2\times R(\lambda_p)$, where λ_p is the peak wavelength. E_a is extracted from the temperature dependence of dark current.

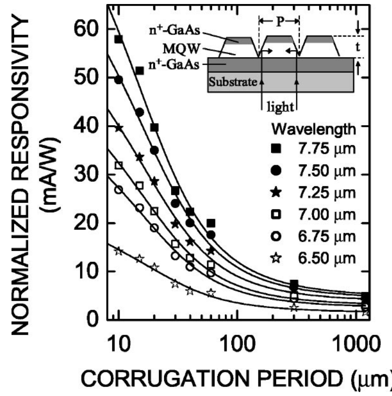

FIG. 3. Normalized responsivity NR of C-QWIPs as a function of C-QWIP period P for different wavelengths. Symbols: Experimental data at 10 K for voltage bias $V_b=6$ V. Lines: least-squares fit of Eq. (1) to the data. Inset: side-view of a C-QWIP with three corrugations. The rays inside the C-QWIP show back illuminated normal incidence light undergoing total internal reflection at the sidewalls to get coupled to the intersubband transitions in the quantum wells.

energy E_a, which is obtained from the temperature dependence of QWIP dark current. E_a is larger for positive V_b than for negative V_b. This is consistent with the fact that the detector has lower λ_c for positive bias than for negative bias. However, E_a extrapolated to zero bias is 163 meV while that given by the cutoff wavelength is 148 meV. This discrepancy may indicate the presence of thermally activated current from the deep donors.

The absence of a peak in responsivity at 10.7 μm for negative V_b could be due to negligible absorption or low gain. In order to improve the detector structure, we need to determine absorption coefficient α and photoconductive gain g as a function of λ for different bias voltages. We use C-QWIPs with different corrugation periods to extract α and g. The details of this characterization technique can be found in Refs. 11 and 12. The side view of a C-QWIP with three periods is shown in the inset of Fig. 3 P is the period of the C-QWIP corrugations; t is the thickness of the top contact layer and active MQW layers that are etched away during processing. We fabricated C-QWIPs with $P=10$, 15, 20, 30, 40, 60, 300, and 1200 μm. ac spectral responsivity was measured at 10 K in the wavelength range 6–12 μm for $-6\ \mathrm{V}\leqslant V_b\leqslant 6$ V. We plot normalized responsivity (NR) as a function of P in Fig. 3 for 6.5 $\mu m\leqslant\lambda\leqslant 7.75\ \mu$m and $V_b=6$ V. NR$=R/r_d$, where r_d is the ratio of the 77 K dark currents of a C-QWIP with period P and a C-QWIP with no corrugations ($P=1200\ \mu$m in our case). Using NR instead of R for data fitting eliminates material variations arising from processing nonuniformities. NR decreases with P as expected because the average optical intensity in a corrugation decreases with P. We fit the following expression to our data:[12]

$$NR(P)=\frac{R(P)}{r_d(P)}=\frac{e}{h\nu}g\frac{1}{P-t}\left(t+\frac{e^{-\alpha P}}{2\alpha}(1-e^{2\alpha t})\right)+R_0\frac{P}{P-t}, \tag{1}$$

where $h\nu$ is the energy of infrared radiation and R_0 is C-QWIP responsivity when P is very large. α, g, and R_0 are fitting parameters, and $t=2.8\ \mu$m is the etch depth for our C-QWIPs. The least-squares fit of Eq. (1) to the data for

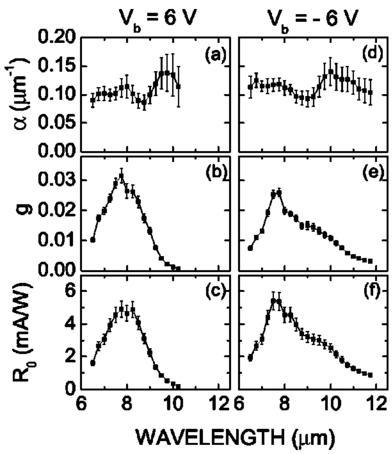

FIG. 4. Wavelength dependence of absorption coefficient α: (a) and (d), gain g: (b) and (e), and R_0: (c) and (f) for bias voltage $V_b = 6$ V and -6 V, respectively. α, g, and R_0 are extracted from fitting Eq. (1) to normalized responsivity data.

different wavelengths is shown in Fig. 3, and we see that Eq. (1) fits the data well. We performed this fitting process for the wavelength range 6–12 μm and bias voltage range of -6 to 6 V and found that the fitting is good.

The detector parameters α, g, and R_0 extracted from the fitting procedure are shown in Figs. 4(a)–4(c) for $V_b = 6$ V and Figs. 4(d)–4(f) for $V_b = -6$ V. We find that α is almost constant, $\approx 0.1\ \mu\text{m}^{-1}$, in the entire wavelength range for both bias voltages. However, there are two small peaks in α around 8 and 9.8 μm for $V_b = 6$ V. For $V_b = -6$ V, α peaks around 10 μm and has a large long-wavelength tail. The detector gain g, on the other hand, has a very pronounced peak at 7.8 μm for both polarities. At $V_b = 6$ V, g decreases sharply for $\lambda > 7.8\ \mu$m and is zero for $\lambda > 10\ \mu$m. However, for $V_b = -6$ V, g decreases slowly beyond 7.8 μm and does not go to zero for long wavelengths. The pronounced peak in g at 7.8 μm and the relatively wavelength insensitive α lead to the bias independent 8 μm peak in R. The line shape of R is determined by the line shape of g. The maximum value of g (≈ 0.03), implies that photoelectrons from one QW, on the average, travel just one period in the MQW structure before being captured by another QW. R_0 and R have the same peak position and similar linewidth for $V_b = \pm 6$ V [see Figs. 1, 4(c), and 4(f)].

The approximately constant value of α as a function of λ indicates inefficient transfer of electrons between the coupled QWs under an applied bias. This is probably due to insufficient voltage drop between the QW pair. The coupled wells have a 50 Å undoped AlGaAs barrier between them and are separated from the next set of coupled wells by a 500 Å undoped AlGaAs barrier. Voltage division between these two barriers leads to less than 10% of the voltage drop across each period of the MQW to drop between the coupled QWs. For example, at $V_b = 6$ V, only 15 mV drops between the coupled wells out of the 160 mV that drops across each period of the MQW. To enhance electron transfer, a larger potential difference is needed between the coupled wells. This can be achieved by growing a thicker AlGaAs barrier between the QW pair.

The presence of the 7.8 μm peak in g for all biases and the lack of any peak in g around 10.7 μm for $V_b < 0$ can be attributed to bound-to-extended state transition in the 8 μm well and bound-to-bound state transition in the 10.7 μm well. The tunneling probability and, hence, photoconductive gain, of the 10.7 μm photoelectrons can be increased by using a thinner layer of $Al_{0.28}Ga_{0.72}As$ in the step barrier between the adjacent periods of the MQW.

In conclusion, we have investigated the presence of the shorter wavelength peak for both bias polarities in two-color QWIPs based on transfer of electrons between coupled QWs under a bias. The detector we fabricated has a peak wavelength of 8 μm for both polarities of V_b but a voltage tunable cutoff wavelength λ_c. λ_c is 9 μm for $V_b > 0$ and 11 μm for $V_b < 0$. We have used C-QWIPs with different corrugation periods to extract absorption coefficient α and photoconductive gain g as a function of wavelength under different operating conditions. We found $\alpha \approx 0.1\ \mu\text{m}^{-1}$ with small peaks at 8 and 9.8 μm for positive V_b and at 10 μm for negative V_b. We also found a peak in g at 7.8 μm for both bias polarities. The QWIP responsivity line shape is determined by the line shape of g. We attribute these observations to insufficient electron transfer between the coupled QWs and to low tunneling probability of the longer wavelength photoelectrons. Based on our understanding of detector parameters α and g, we proposed a modified QWIP structure that should lead to complete switching of spectral responsivity peak when the polarity of the bias voltage is reversed.

The work at Princeton University is supported by the Army Research Office and the National Science Foundation.

[1] K. K. Choi, *The Physics of Quantum Well Infrared Photodetectors* (World Scientific, River Edge, NJ, 1997).
[2] C. J. Chen, K. K. Choi, W. H. Chang, and D. C. Tsui, Appl. Phys. Lett. **72**, 7 (1998).
[3] A. Kock, E. Gornik, G. Abstreiter, G. Bohm, M. Walther, and G. Weimann, Appl. Phys. Lett. **60**, 2011 (1992); I. Grave, A. Shakouri, N. Kuze, and A. Yariv, *ibid.* **60**, 2362 (1992).
[4] S. D. Gunapala *et al.*, IEEE Trans. Electron Devices **47**, 963 (2000); M. Sundaram *et al.*, Infrared Phys. Technol. **42**, 301 (2001).
[5] K. K. Choi, B. F. Levine, C. G. Bethea, J. Walker, and R. J. Malik, Phys. Rev. B **39**, 8029 (1989).
[6] B. F. Levine, C. G. Bethea, V. O. Shen, and R. J. Malik, Appl. Phys. Lett. **57**, 383 (1990).
[7] E. Martinet, F. Luc, E. Rosencher, P. Bois, and S. Delaitre, Appl. Phys. Lett. **60**, 895 (1992); E. Martinet, E. Rosencher, F. Luc, P. Bois, E. Costard, and S. Delaitre, *ibid.* **61**, 246 (1992).
[8] K. K. Choi, B. F. Levine, C. G. Bethea, J. Walker, and R. J. Malik, Appl. Phys. Lett. **52**, 1979 (1988).
[9] V. Berger, N. Vodjdani, P. Bois, B. Vinter, and S. Delaitre, Appl. Phys. Lett. **61**, 1898 (1992).
[10] C. J. Chen, K. K. Choi, M. Z. Tidrow, and D. C. Tsui, Appl. Phys. Lett. **68**, 1446 (1996).
[11] C. J. Chen, K. K. Choi, L. Rokhinson, W. K. Chang, and D. C. Tsui, Appl. Phys. Lett. **75**, 3210 (1999).
[12] K. K. Choi, C. J. Chen, and D. C. Tsui, J. Appl. Phys. **88**, 1612 (2000).