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Two-Dimensional Bi-Periodic Grating Coupled One- and Two-Color Quantum Well Infrared Photodetectors

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Multiple quantum well infrared photodetectors (QWIPs) with two-dimensional bi-periodic grating couplers have been demonstrated. For one-color QWIPs, the response linewidths of such QWIPs are found to be much wider than those of conventional grating coupled QWIPs. The bi-periodic gratings have also been applied to two-color QWIPs to separately optimize the absorption at two wavelength bands. The large difference in responsivities at the two wavelength bands for devices with single period gratings can be greatly reduced with the use of bi-periodic gratings.

1. TEXT

Multiple quantum well infrared photodetectors (QWIPs) based on III-V compound semiconductors have attracted a lot of attention in recent years. The increased interests in QWIPs are due to the possibility of producing high performance, large area, highly uniform and low cost two-dimensional image arrays[1-3] as a result of mature growth and the processing technologies of III-V compound materials. According to the selection rules of quantum mechanics, the electrons in quantum well do not absorb radiation incident normal to the surface. Because of this, grating couplers are usually used to couple the normal incident radiation into the quantum wells. The spectral response of grating coupled QWIPs largely depend on the period of the grating and the quality of the grating. Because the grating is itself a filter, the spectro-response can be further narrowed from an already narrow spectrum of QWIPs. Variation in grating quality or period can result in nonuniformity in response across an array. It is therefore desirable to have a wider grating response to eliminate the loss of IR. We have used one-dimensional (1D) bi-periodic grating couplers to increase the width of spectroresponse of one-color QWIPs.[4] Recently, two-dimensional (2D) gratings have been studied theoretically and experimentally.[5] It is shown that the efficiency of 2D grating is better than that of 1D grating, because 2D grating can scatter both transverse electric (TE) and transverse magnetic (TM) polarization components of the incident waves. Besides, 2D gratings also give the designer a freedom to design two different periods in the x and y directions. In this work, we have used such gratings with two different periods to cover a wider spectral range for QWIPs. In addition, we have also used 2D bi-periodic gratings for two-color QWIPs. Conventional single period grating couplers can only match one band of two- or multi-color QWIPs, so the absorptions at other bands are not optimized. In this work, we used two different grating periods in the x and y directions to separately match the desired two color bands. The absorptions at both wavelength bands were thus optimized.

The QWIPs were grown by molecular beam epitaxy (MBE) on (100) semi-insulating GaAs substrates. For one-color QWIPs, the layers consisted of, from the substrate side, a 1.1 μm n^+ bottom contact layer, a fifty period multiple quantum well structure with 40 Å GaAs wells sandwiched between 400 Å $Al_{0.26}Ga_{0.74}As$ barrier layers, and a 1.4 μm n^+ top contact layer. For two-color QWIPs, the quantum wells between two n^+ 1.2 μm contact layers, consisted of two stacks with ten quantum wells each. The first stack was designed as a long wavelength QWIP, with each period of quantum wells consisting of a 40 Å GaAs well and 300 Å $Al_{0.27}Ga_{0.73}As$ barriers. The second stack was designed as a middle wavelength QWIP, with each period of quantum wells consisting of a 45 Å $In_{0.18}Ga_{0.82}As$ well and two barriers. The inner barriers were 15 Å $Al_{0.41}Ga_{0.59}As$ and the outer barriers were 300 Å $Al_{0.27}Ga_{0.73}As$. The wells and the contact layers for the two devices were Si-doped with doping concentrations of $1x10^{18}$ cm^{-3} and $2x10^{18}$ cm^{-3}, respectively.

After growth, 200 μm square mesas were defined by chemical etching down to the n^+ bottom contact layer. Gratings were chemically etched through a photoresist mask on top of the mesas. Devices with two-dimensional single-periodic and bi-periodic gratings were fabricated on the same wafer at the same time. The depth of these gratings was about 0.7 μm. Au/Ge was evaporated onto the top of each mesa and the n^+ bottom contact layer for ohmic contacts. The QWIPs were irradiated with IR from the back side with normal incidence. The spectral response of the QWIPs was measured at 80 K using a current preamplifier and a Nicolet Fourier transform infrared spectrometer. The responsivity was measured at 80 K by the standard lock-in technique using a 970 K black-body source chopped at 1 KHz. The QWIPs with different types of gratings were measured under the same conditions.

The energy band diagrams of our one-color QWIPs and two-color QWIPs are shown in Figure 1(a), and 1(b), repectively. The intersubband transition schemes for one-color and two-color absorptions are also shown in the figures. The intersubband transition of the GaAs/AlGaAs quantum well is from bound to continuum state, but that of the InGaAs/AlGaAs quantum well is from bound to quasicontinuum state.[6,7] Figure 2 shows a diagram of a 2D grating of square symmetry. The transverse period is X, and the longitudinal period is Y. Figure 3(a), 3(b), and 3(c) show the spectral responses of the QWIPs at 3.5 V with 2D gratings of (2.7 μm, 2.7 μm), (3.0 μm, 3.0 μm), and (3.2 μm, 2.8 μm), respectively, where (a, b) gives the periods in X and Y directions, respectively. The peaks of photocurrent spectra with periods of 2.7 μm and 3.0 μm are at 8.2 μm and 8.7 μm. The position of the response peak moves to longer wavelengths as the period increases, as seen in Fig. 3 (a) and 3 (b). The 3.0 μm grating yields the highest response peak, since the grating response best matches the natural response of the QWIPs. Because of the filtering effect of gratings, the spectral response of grating coupled QWIPs is usually narrower than the natural response curve of the devices. The measured response linewidth of the QWIPs with 2.7 μm and 3.0 μm gratings are 1.7 μm. However, the linewidth of the QWIP with bi-periodic gratings of (3.2 μm, 2.8 μm) is 2.2 μm, which is significantly larger than those of devices with single period gratings. The responsivity of the devices across the wafer is 0.4 A/W and shows better uniformity which is attributed to the wide responses that can better tolerate the nonuniformity in material growth and grating process.

Figure 4(a), 4(b), and 4(c) show the spectral responses of two-color QWIPs at different biases (with mesa top positive) with 2D gratings of (2.7 μm, 2.7 μm), (3.0 μm, 3.0 μm), and (2.7 μm, 1.8 μm), respectively. The response peaks of the two-color QWIPs are near 5.3 μm, and 8.1 μm. The 5.3 μm band turns on first (at low biases) because their quantum wells have high resistance in comparison with the 8.1 μm band's.[8-9] The responsivities of the three types of grating are listed in Table I and Table II. The 5.3 μm peak responsivity measured at 2 V is about 0.15 A/W for single-periodic gratings, and 0.3 A/W for bi-periodic gratings. The 8.1 μm peak responsivity measured at 3.5 V is about 0.31 A/W for single-periodic gratings, and 0.22 A/W for bi-periodic gratings. With bi-periodic gratings, the responsivity for the 5.3 μm band is two times as large as that with single-periodic gratings. This is because the grating period of 1.8 μm in the Y direction matches the natural response of 5.3 μm. So the incident radiation at this wavelength is efficiently coupled into the quantum wells resulting in higher quantum efficiency. For the long wavelength peak at 8.1 μm, the gratings of 2.7 μm period in the X direction match the natural response. So the couplings of IR radiation at these two wavelength bands are optimized. With single-periodic gratings, because the grating period can match only one wavelength band (in our case, the long wavelength band), the coupling of the light with wavelengths not matching the grating period is greatly reduced resulting in a very large difference in responsivities at the two wavelength bands.

In summary, we have demonstrated the use of bi-periodic, two-dimensional gratings for coupling IR radiation into one-color and two-color QWIPs. Because of the flexibility of design in such gratings, we have applied such gratings to increase the width of the spectral response of single colored QWIPs from 1.7 μm to 2.2 μm. The influence of variation of material and grating quality on the performance of QWIPs can be eliminated. Additionally, for two-color QWIPs, we also have applied bi-periodic gratings to separately optimize the two wavelength bands. The large difference in responsivities at the two wavelength bands for devices with single period gratings can be greatly reduced with the use of bi-periodic gratings.

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2. FIGURES AND TABLES

Table I
The 5.3 μm responsivities of three types of two-dimensional grating on two-color quantum well infrared photodetectors

Voltage (V)	Period=2.7μm R(A/W)	Period=3.0μm R(A/W)	Bi-Period R(A/W)
1.0	0.07	0.08	0.23
2.0	0.16	0.14	0.30
3.5	0.06	0.06	0.16

Table II
The 8.1 μm responsivities of three types of two-dimensional grating on two-color quantum well infrared photodetectors

Voltage (V)	Period=2.7μm R(A/W)	Period=3.0μm R(A/W)	Bi-Period R(A/W)
3.5	0.35	0.27	0.22
4.0	0.31	0.31	0.22

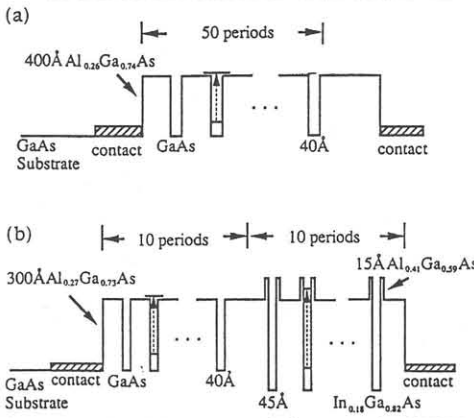

Fig.1 The energy band diagrams of (a) one-color QWIPs, and (b) two-color QWIPs.

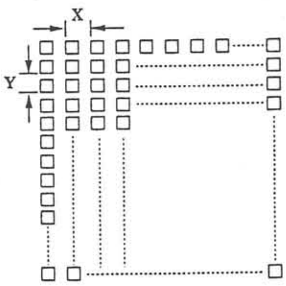

Fig.2 Structure of a 2D grating of square symmetry. The transverse period is X, and the longitudinal period is Y.

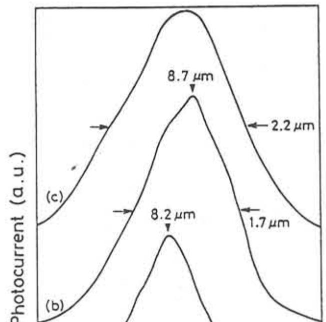

Fig.3 The spectral responses of the QWIPs at 3.5 V with 2D gratings of (2.7 μm, 2.7 μm), (3.0 μm, 3.0 μm), and (3.2 μm, 2.8 μm) in (a), (b), and (c), respectively, where (a, b) gives the periods in X and Y directions, respectively.

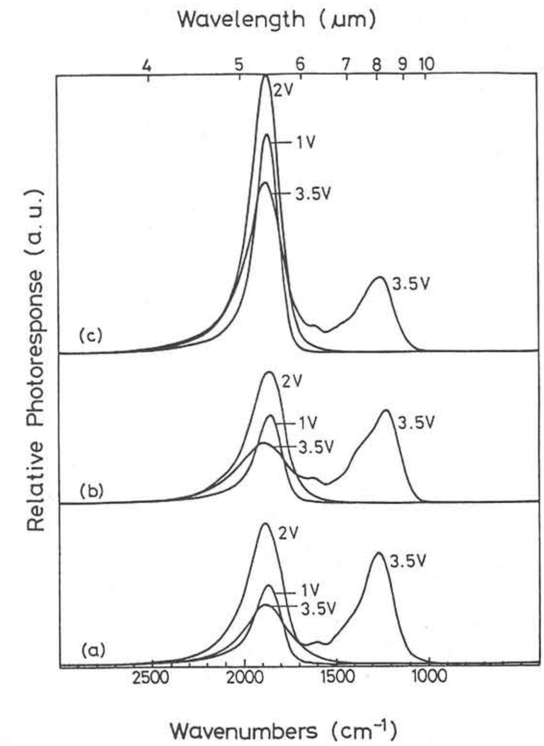

Fig.4 The spectral responses of the two-color QWIPs at different biases with 2D gratings of (2.7 μm, 2.7 μm), (3.0 μm, 3.0 μm), and (2.7 μm, 1.8 μm) in (a), (b), and (c), respectively.

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