Effect of indium content on the normal-incident photoresponse of InGaAs/GaAs quantum-well infrared photodetectors

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Longwavelength InGaAs/GaAs quantum-well infrared photodetectors with indium contents ranging from 25% to 40% have been grown and characterized. Material quality has been assessed by photoluminescence and transmission electron microscopy. Intersubband photocurrent, excited by polarized (TE or TM) infrared light, has been analyzed in order to determine the responsivity for normal-incident radiation. It is found that the TE to TM responsivity ratio is lower than 10% in all the samples studied. By changing the indium content from 25% to 40%, the increase in the TE to TM photoresponse ratio is as low as 3%. Our results are opposite to previous reports of experimental observation of significant TE-polarized light absorption. However, the low efficiency for normal-incident radiation agrees with various theoretical predictions. [DOI: 10.1063/1.1365951]

The rapid development in conventional AlGaAs/GaAs quantum-well infrared photodetectors (QWIPs) based on intersubband transitions has allowed to produce large-format and high-uniformity focal-plane arrays for imaging systems.[1] For *n*-type QWIPs, in-plane polarized optical intersubband transitions are forbidden in a single-band effective-mass envelope-function model.[2] Based on this assumption, optical diffraction gratings are necessary in order to couple normal-incident radiation, thus making the technological process more complicated and expensive.

However, experimental observation of significant normal-incident light absorption (TE to TM ratio as high as 40%) has been reported for grating-free $In_{0.3}Ga_{0.7}As$-based QWIPs (Refs. 3 and 4) and has been attributed to band-mixing effects. By contrast, Liu, Buchanan, and Wasilewski,[5] using a special measurement arrangement to avoid macroscopic light-scattering effects that might overestimate the TE-polarized response, have compared the TE to TM photoresponse ratio of both $In_{0.1}Ga_{0.9}As$-well- and a GaAs-well-based QWIPs and obtained ratios of 3% and 0.2%, respectively. Also in this case, the higher TE to TM ratio for the InGaAs QWIP is thought to be a consequence of band-mixing effects, which are expected to be more relevant as the indium content of the alloy increases.

In this work, we have grown and characterized a series of long-wavelength InGaAs/GaAs QWIPs with indium content ranging from 25% to 40% with the purpose of studying the band-mixing effects on normal-incident light absorption in structures with enhanced coupling between the valence and conduction bands due to the reduction of band-gap energy. Our results clearly show that the TE to TM signal ratio is not higher than 10% in any case. Moreover, this ratio is only very slightly affected by the enhancement of band-mixing effects corresponding to an increase in the indium content from 25% to 40%.

Samples were grown by solid-source molecular-beam epitaxy on (100) semi-insulating GaAs substrates. The multiple-quantum-well (MQW) structure consists of ten periods of $In_xGa_{1-x}As$-doped wells separated by 500 Å GaAs barriers. Indium contents are $x=0.25$, 0.3, 0.35, and 0.4 and corresponding well widths are 55, 40, 30, and 30 Å. The wells are Si doped to $2\times10^{18}\,cm^{-3}$ in the central 20 Å according to previous calibration experiments on GaAs layers. The MQW structure is sandwiched between 0.5 μm GaAs buffer and 0.3 μm GaAs cap layers both Si doped to $2\times10^{18}\,cm^{-3}$. The GaAs growth rate, determined by reflection high-energy electron diffraction (RHEED) oscillations, was 1 μm/h for the whole structure. Indium contents were calibrated using InAs RHEED oscillations on an InAs substrate. High-beam-equivalent pressures of As_4 and low substrate temperatures for the active region were used to minimize indium segregation and island formation. Previous to the growth of the QWIP structures, a test structure with the same InGaAs layer was grown in order to ensure that the RHEED pattern did not show any trace of three-dimensional (3D) growth.

200 μm circular mesas were fabricated by standard photolithography and wet-chemical etching. To make the contacts, Au/AuGe ring metallization was deposited on top of the mesas and an alloyed $In_{0.98}Sn_{0.02}$ dot on the bottom. A 45° facet was polished at both ends of the sample so as to couple normal-incident infrared radiation. The backside was also mechanically polished down to a thickness of 300 μm.

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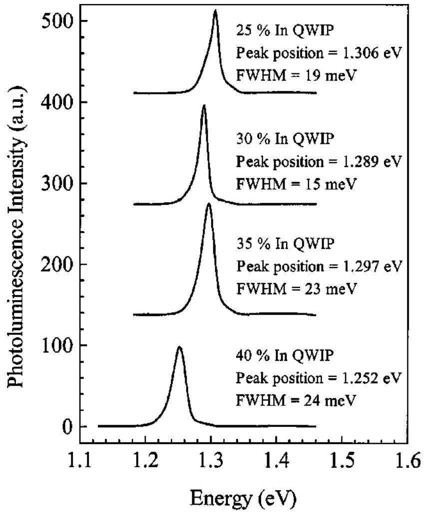

FIG. 1. Low-temperature (25 K) photoluminescence spectra of the InGaAs/GaAs QWIPs with different indium contents. The excitation power was a He–Ne laser ($\lambda = 632.8$ nm) and the optical power was 1 mW.

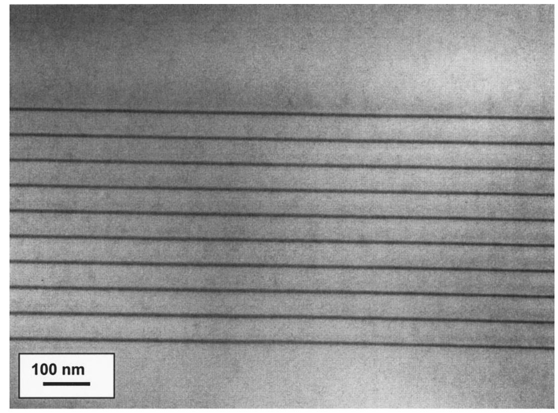

FIG. 2. Dark-field cross-sectional TEM image with 200 reflection of the $In_{0.35}Ga_{0.65}As$/GaAs QWIP showing the structural quality of the QWs.

The detector was placed as close as possible to the edge of the 45° bevelled facet to allow direct illumination, avoiding possible scattering effects after reflections inside the waveguide.

The optical quality, In content, and well thickness of the samples were assessed by photoluminescence (PL) spectroscopy. The 25 K PL spectra of the four samples are shown in Fig. 1.

The measured PL peak positions are slightly blueshifted with respect to those calculated according to our simulation for square wells. For the QWIPs with 25% and 30% indium content, the peak position is close to the simulated value in less than 10 meV. This shift could be explained by the uncertainty in the growth rate calibrations. However, for the 35% and 40% indium content QWIPs, the energy differences between experimental and calculated transitions are 15 and 18 meV, respectively. For such high indium contents, surface segregation of indium limits the formation of abrupt interfaces, modifying the ideal square conduction-band profile and causing a blueshift of the PL peak position.[6] The indium content and quantum-well thickness required to fit the experimental PL peak are 1% lower and 1 ML thinner, respectively, than the nominal values. Therefore, the quantum-well nominal parameters are not expected to differ much from the real ones for the 35% and 40% indium QWIPs. Moreover, the good quality of the samples is supported by the intensity and full width at half maximum (FWHM) of the PL peaks corresponding to the Si-doped quantum wells. (The FWHM is lower than 25 meV in any case and as low as 15 meV for the 30% QWIP.)

In order to evaluate the structural quality of the QWIPs, a transmission electron microscopy (TEM) study was performed. The TEM observations revealed no dislocation evidence for all the QWIP samples. This result suggests a misfit dislocation density below $10^4\ \mathrm{cm}^{-1}$, and the quantum wells are elastically strained without plastic relaxation (Fig. 2). Moreover, a 3D growth onset could only be detected in the 40% indium content QWIP. The importance of this interface roughness is crucial when trying to get a reliable TE to TM ratio since the enhancement of the TE photoresponse by microscopic scattering due to interface roughness has been reported.[7,8]

In the photocurrent measurements, the light coming from a SiC emitter source at 1000 K was dispersed by a grating monochromator and the electrical signal detected with a lock-in technique. The responsivity spectra were obtained from the photocurrent intensities and the spectral distribution of photon flux shinning the detector, as measured by a calibrated pyroelectric detector. A ZnSe wire-grid polarizer, placed after the monochromator, allowed us to separate the contributions of the *S*-polarized light (equivalent to normal-incident radiation or TE) and *P*-polarized light (TE and TM polarization modes in equal shares) to the responsivity spectra. From the ratio between *S* and *P* contributions, we obtained the TE to TM signal ratio. Since the reflection coefficient for both *S* and *P* polarizations is the same in magnitude when illuminating the 45° facet, this ratio is

$$\mathrm{TE/TM} = 1/[2 \times (R_P/R_S) - 1],$$

where R_P is the responsivity for *P*-polarized light and R_S for *S*-polarized light.

Figures 3(a) and 3(b) show the responsivity spectra of

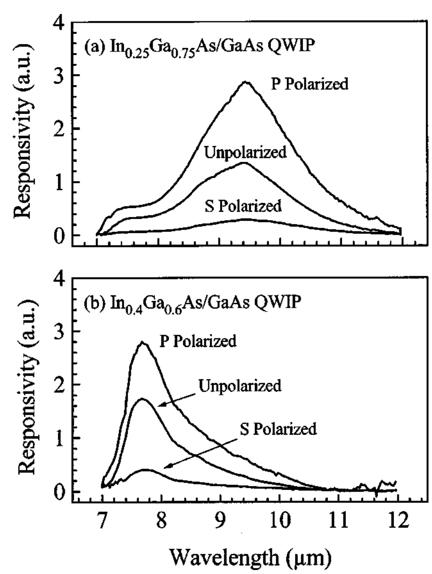

FIG. 3. Responsivity spectra for unpolarized, *S*-polarized, and *P*-polarized light at 30 K of (a) an $In_{0.25}Ga_{0.75}As$/GaAs QWIP and (b) an $In_{0.4}Ga_{0.6}As$/GaAs QWIP.

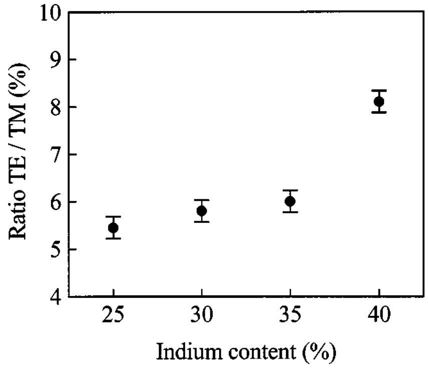

FIG. 4. TE to TM responsivity ratio for QWIPs with different indium contents. For each content the value is the average among several devices of the same wafer.

the 25% and 40% indium content QWIPs at 25 K for unpolarized, *S*-polarized, and *P*-polarized light. The responsivity spectra for samples with 30% and 35% indium content are very similar, in relative TE/TM peak intensity and detection wavelength, to those in Fig. 3(a). In Fig. 3(b) we notice a blueshift in the intersubband transition energy of the sample with 40% indium content. To obtain the peak detection in the same wavelength as QWIPs with lower indium content, the well thickness should be narrower (about 25 Å instead of the nominal 30 Å). Nevertheless, our interest here is focused on the TE/TM responsivity ratio and its variation with indium content.

In Fig. 4, we summarize the values of the TE to TM responsivity ratio of all the detectors at the bias voltage of the maximum signal. Various devices have been measured on each sample and average values with the associated error bars are plotted. The most significant result is that the TE to TM ratio is not higher than 10% for all the indium contents studied. It must be noted that we have not avoided all the possible scattering effects (mesa edges, reillumination by reflected light) that may turn TE-polarized light into TM-polarized light. This could lead us to overestimate the real TE to TM ratio, which may be even lower than the measured values.

Equally interesting is the observation of only a slight increase in the TE to TM ratio, not higher than 1%, when the In content is increased from 25% to 35%. This clearly shows that the variation in band mixing does not have any significant effect on the normal-incident radiation absorption. Regarding the sample with the highest indium content (40%), a slight TE to TM ratio increase (3%) has been measured (Fig. 4). Although this increase could be related to a higher contribution of band mixing, we believe it is rather associated with the rough interface observed in this sample by TEM, which produces microscopic scattering, thus leading to an overestimation of the TE photoresponse.

Contrary to our observations, Refs. 3 and 4 report the measurement of strong normal-incident light absorption in 30% InGaAs-based QWIPs. Reference 9 points out that intersubband optical transitions are both TM and TE polarization active. Both experimental and theoretical results are explained in terms of band mixing. However, our small values for the TE to TM ratio agree with the theoretical calculations reported by Yang[10] and Pan and Fonstad,[11] who, taking into account multiband coupling effects, predict a very weak intersubband absorption of normal-incident light.

In conclusion, the TE to TM responsivity ratio of high-quality InGaAs/GaAs QWIPs with high indium content has been found to be lower than 10%. An indium content increase from 25% to 40% only causes a 3% increase in this ratio, which questions the importance of band-mixing effects for normal-incident radiation absorption in *n*-type InGaAs-based QWIPs. Our results also suggest that this type of QWIP does not have the intrinsic capability for normal-incident detection and that the ultimate reason for the efficient TE response is still under discussion.

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