Growth optimization of InGaAs quantum wires for infrared photodetector applications

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We studied the quantum wire photodetector (QRIP) structures with an InGaAs quantum wires (QWRs) active region formed by the strain-induced lateral ordering (SILO) process. The InGaAs multiple layer QWR structure maintains a small total strain due to the strain-balanced nature of the SILO process. The effects of growth temperature and layer structures on the QWR formation are studied using photoluminescence and transmission electron microscope measurements. High-resolution x-ray diffraction studies on QRIP structures consisting of 20 QWR layers confirmed the strain-balanced property of SILO-based structures. © 2006 American Vacuum Society. [DOI: 10.1116/1.2190665]

I. INTRODUCTION

There has been a need for detectors in the infrared (8–12 μm) spectral region for applications such as imaging, remote sensing, and IR spectroscopy. At present, HgCdTe alloy based on band-to-band transition is the most often used semiconductor for IR photodetectors. Due to the material instability resulting from the weak Hg–Te bond, problems of production uniformity and yield remain unresolved. For this reason, efforts have been shifted toward semiconductor alloys based on band-to-band transition is the most often used semiconductor for IR photodetectors. Due to the material instability resulting from the weak Hg–Te bond, problems of production uniformity and yield remain unresolved. For this reason, efforts have been shifted toward semiconductor alloys based on band-to-band transitions in quantum confined structures. Quantum well infrared photodetectors (QWIPs) have been widely investigated over the last decade and have made substantial progress toward detection of infrared radiation. However, QWIPs are insensitive to normal incident radiation due to the selection rules. A grating layer on top of the detector structure or using off-normal illumination is commonly employed to couple p-polarized light into the detectors.1,2 A more efficient way to detect the near normal incident light with the intersubband transitions is to utilize the quantum wire (QWR) and quantum dot (QD) nanostructures.

The quantum dot infrared photodetectors (QDIPs), owing to the three-dimensional quantum confinement of the carriers in QDs, have been the subject of extensive research to replace QWIPs.3–6 However, there is no report on the development of quantum wire infrared photodetectors (QRIPs). Quantum wires like quantum dots also offer a solution to the problem of normal-incidence polarization. QRIPs, compared with QWIPs, are also expected to display low dark current and better response at elevated temperatures due to the suppressed electron-phonon scattering in the two-dimensional confinement nanostructures.7–9 Although QWRs have a shorter intersubband relaxation time compared with QDs, the band filling effect in QWRs is mitigated to allow extra carriers to be involved in the photocurrent response.10 Therefore, the QRIP technology is promising to compete with QWIPs.

In this work, we present results concerning the influence of growth parameters on the formation and quality of InGaAs QWRs for infrared photodetector applications. The InGaAs QWRs are formed by the strain-induced lateral-layer ordering (SILO) process developed by Cheng et al.11 The SILO process is a completely in situ, one-step molecular beam epitaxy (MBE) method for producing QWR structures with a high linear density of wires on (100)-oriented substrates. The details of the SILO process are described elsewhere.11,12 In short, by depositing a short-period superlattice (SPS) of m monolayers of InAs with a lattice constant larger than InP, and n monolayers of GaAs with a lattice constant smaller than InP, a Ga/In composition modulation forms along the [110] direction and the long axis of the islands is along the [110] direction.6 By depositing the SPS region between larger band gap materials, QWRs are formed. We studied the dependence of structural and optical properties of InGaAs QWRs on the growth temperature and SPS layer structure. We further optimized the design by varying the Al0.24Ga0.24In0.52As barrier thickness. A correlation between the optical quality and the structural variations is observed, and the optimized QRIP design and growth conditions are determined.

II. EXPERIMENT

The QRIP test samples are grown on n-type InP (001) substrates via solid-source MBE under an As pressure of 5 × 10−6 Torr. The surface oxides desorption temperature of InP substrates is set to be 500 °C. The active region consists of three QWR layers with ten pairs of (GaAs)m/(InAs)n SPS in each layer, and each QWR layer is confined by 500 Å barriers of Al0.24Ga0.24In0.52As. Within each QWR layer, a ratio of m/n = 1.8 ML/2.35 ML, is used in the first two pairs of (GaAs)m/(InAs)n SPS to provide extra strain for the QWR formation. The m/n ratio is kept at a constant of 2.0 ML/2.25 ML in the remaining eight SPS pairs. Only the middle six SPS pairs are doped with Si (~2 × 1018 cm−3) to prevent the
provides a high surface mobility for the adatoms resulting in QRIP sample grown at 530 °C, the high growth temperature graphs displayed in Figs. 2

III. RESULTS AND DISCUSSIONS

A. Growth temperature effect

The temperature dependent surface diffusion of the adatoms during growth affects the structural and optical properties of QWRs. Three samples are grown at different substrate temperatures of 500, 510, and 530 °C. Figure 1 shows the 300 and 77 K PL spectra of QRIP test samples grown at these temperatures. The 77 K PL peak wavelengths are about 1.591, 1.605, and 1.605 μm, and the linewidths are 30, 27, and 38 meV for the SPS structures grown at 500, 510, and 530 °C, respectively. The difference between wavelength shifts and the linewidth variations of QRIp samples clearly indicates that there is temperature dependence in QWR formation. It is clear from the dark field [110] XTEM micrographs displayed in Figs. 2(a)–2(c) that all three QWR structures demonstrate a lateral composition modulation along [110] in each QWR layer. The bright fringes correspond to In-rich In$_{0.48}$Ga$_{0.52}$As while the dark fringes are Ga-rich In$_{0.48}$Ga$_{0.52}$As. For the QRIP sample grown at 500 °C, a weak lateral composition modulation occurs as indicated by the XTEM micrograph in Fig. 2(a). Comparing with QWRs grown at 500 °C, the lateral composition modulation is stronger for the sample grown at 510 °C. Furthermore, the QRIP sample displays a band gap anomaly where the 77 K peak PL peak wavelength almost overlaps with the 300 K peak PL wavelength. These results agree well with what would be expected from SILO-grown materials. For the QRIP sample grown at 530 °C, the high growth temperature provides a high surface mobility for the adatoms resulting in a long diffusion length. This is evident from its broader and fewer periodic fringes in the XTEM image shown in Fig. 2(c). The broad linewidth and weak intensity of the 77 K PL spectrum shown in Fig. 1(c) also faithfully reflect the irregularity of the QWRs. It is clear from Fig. 2(c) that strain propagating between neighboring QWR layers, through the barrier layer, due to strengthened lateral composition modulation is an unwanted property in the multilayer growth for photodetector applications. This series of measurements determines that the optimal growth temperature for preparing InGaAs QRIP using the SILO process is 510 °C.

B. Multiple (20) QWR layer growth

In order to increase the photoresponse of photodetectors, the active region with 30–100 layers of quantum wells is a common design in QWIPs. Due to the limitation of strain relaxation-related defects, QDIPs regularly consist of only 10–20 QD layers in the active region. However, SILO-based InGaAs QWRs possess a near zero total strain due to the strain-balanced nature of the SILO process. It can be observed from the XTEM image in Fig. 2(b) that QWR formation in layers separated by 500 Å barriers is basically independent to each other with a minimum strain propagation. Therefore, a 20-layer QRIP sample similar to the basic test structure is grown at the optimized temperature of 510 °C. To verify the QWR formation, the PPL spectrum of the 20-layer QRIP sample is measured and displayed in Fig. 3. It is
clear that the PL spectra are highly polarized in [110] (perpendicular to QWRs) direction at both 300 and 77 K. This large polarization anisotropy of PL intensity comes from the enhanced nonlinear optical properties associated with decreased crystal symmetry induced by strain and the additional degree of confinement in the [110] direction.\textsuperscript{15} The XTEM image taken from the 20-layer QRIP structure is shown in Fig. 4. The top edge of each QWR layer is slightly nonplanar caused by the lateral composition modulation.\textsuperscript{11,16} The lattice constant varies across the growth plane resulting in areas of lattice compression and lattice dilation. The lateral composition fluctuation in the QWR layer can propagate into the quaternary barrier as observed previously.\textsuperscript{17} By using the optimized strain design in the SILO process for the growth of QWR layers, the lateral composition variation extends only slightly into barrier layers. Therefore, no significant strain propagation throughout the whole structure is observed and no vertical alignment of QWRs can be clearly distinguished from the XTEM micrograph. The uniform QWR layer growth over the whole structure implicates that the stacking of more than 20 QWR layers in the active region without deteriorating the material quality is possible. The strain-balanced nature of the 20-layer SILO-based QRIP structure is further confirmed by the HRXRD spectrum shown in Fig. 5(a). In Fig. 5(b) a simulated rocking curve of the 20-layer QRIP structure without including strain from QWR formation was shown. The high frequency satellite
peaks are due to the periodic 20 QWR layers, and the low frequency satellite peaks are originated from the SPS within each QWR layer. The large number of the high frequency satellite peaks seen in the measured rocking curves attests to the structural integrity of these QWR layer/barrier repetitions. The nearly symmetric distribution of satellite peaks in Fig. 5(a) on both sides of the InP substrate peak and the almost match of satellite peak positions to those in Figure 5(b) indicate that the entire structure is subject to an insignificant amount of strain. In addition, the periodicity of SPS pairs can be clearly identified on the right side of the spectrum as undulations with a larger period in Fig. 5(a). However, it is slightly distorted and its peak position is off relative to that in Fig. 5(b), indicating the existence of a slightly lattice mismatch in the barrier layers and the lateral composition modulation within the QWR layer.

C. Barrier thickness effect

It is observed from the reflection high-energy electron diffraction patterns during the QWR growth and cross-sectional TEM images (Fig. 5) that the strain generated by QWR layers can be largely relaxed within a barrier thickness of 300 Å. Therefore, a 20-layer QRP sample with a barrier thickness of 300 Å, keeping everything unchanged, is grown to minimize the thickness of the whole device structure. A reference QRP sample with a barrier thickness of 500 Å was also grown. The two 20-layer QRP samples are both grown at 510 °C under an As overpressure of $1 \times 10^{-6}$ Torr. The room temperature and 77 K PPL spectra of these samples are shown in Fig. 6. Both samples show comparable performance in 77 K PL linewidth of 39 meV and the degree of polarization, except for the sample with a thinner barrier that showed a better PL intensity. The near identical redshift of the PL peak at 77 K relative to 300 K for the two samples indicates that they have similar total strain in the QWR structure. The improved PL intensity in the structure with thinner barriers can be reasonably inferred to the better absorption of the excitation light source. Overall, the two designs with different barrier thickness of 300 and 500 Å have similar performance and both can be used in the detector structure.

IV. CONCLUSION

In summary, we have investigated the dependence of the optical properties of InGaAs QWRs formed by the SILO process on the MBE growth temperature and SPS layer structures. The optimized growth temperature is determined to be 510 °C under an As overpressure of $5 \times 10^{-6}$ Torr. Through XTEM, PPL, and HRXRD measurements, it is confirmed that the SILO-based InGaAs QRP structures with strain-balanced design can maintain good optical quality and uniform layer structure in multiple (>20) layer structures. The incorporation of a larger number of QWR layers in photodetectors can therefore be achieved. Furthermore, by reducing the barrier thickness from 500 to 300 Å, the total thickness of the entire structure can be reduced without degradation of the total strain and the optical quality of the QRP structures.
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10Paul Harrison, Quantum Wells, Wires and Dots: Theoretical and Computational Physics of Semiconductor Nanostructures, 2nd ed. (Wiley, New York, 2005), Chap. 3.