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Investigation of the recrystallization of amorphized InP layers using photoacoustic technique

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The annealing behavior of the amorphous layers produced by heavy Si⁺ implantation in InP substrates is studied using the piezoelectric PAS with implantation energy as a parameter. The usefulness of PAS is elucidated for investigating depth profile of disorder (defects) in implanted layers and its annealing characteristics.

1. INTRODUCTION

Photoacoustic spectroscopy (PAS) has recently been recognized to be a promising method for investigating nonradiative transition processes in semiconductors. As defect centers produced by ion implantation behave in general as nonradiative centers, PAS is expected to be useful for characterizing these defects. Although there are various detection techniques in PAS, piezoelectric transducer technique which was developed by Jackson and Amer [1] has attracted much attention because its arrangement is more simple and its ambient noise is much smaller than those of microphone technique. In addition, these transducers have usually a wide frequency response and can be used over a wide range of temperature and pressure.

Amorphous layers produced by Si⁺ ions implantation in InP have been investigated by Rutherford backscattering (RBS) [2-4] and transmission electron microscopy (TEM) [5] and Raman scattering [6] measurements. We have so far investigated the annealing behavior of damaged layers by ion implantation in Si [7], GaAs [8] and InP [9] by the piezoelectric PAS.

In this report, the rapid thermal annealing (RTA) behavior of the amorphous layers produced by heavy Si⁺ implantation in InP substrates is studied using the piezoelectric PAS with implantation energy as a parameter.

2. EXPERIMENTAL

Substrates for implantation were semi-insulating ($10^7 \Omega \text{ cm}$) Fe doped InP grown by the liquid-encapsulated Czochralski (LEC) method. Si⁺ ions were implanted into the substrates with a fluence of 10^{15} cm^{-2} which is sufficient to produce amorphous layers and at energies of 35, 50, 100, 200 and 300 keV, respectively [2-6, 9]. Isochronal annealing was carried out for 10 sec up to 800 °C in an argon atmosphere using an infrared imaging furnace.

The PA measurements were carried out at room temperature. The light source used was a 150 W halogen lamp and a light-chopping (modulation) frequency was at 350 Hz. The light which was passed through a monochromator was incident on the samples. The PA signals were detected by a PZT (Tokin Co., Ltd. NPM, N-21) transducer directly attached to the near-edge of the rear surface of the samples with a silicone grease. The PA signals were measured by a lock-in amplifier.

3. RESULTS AND DISCUSSION

Figure 1 shows the PA spectra near the band-edge E_g ($= 1.34 \text{ eV}$) of unimplanted and Si⁺ implanted InP with a fluence of 10^{15} cm^{-2} at energies of 35, 50, 100, 200 and 300 keV,

Figure 1 The PA spectra near the band-edge of unimplanted and Si⁺-implanted InP with implantation energy as a parameter.

respectively. All of the PA spectra showed an abrupt change below the E_g (which corresponds to the wavelength 930 nm) [10]. The PA signal intensity at the shorter wavelength side than the wavelength of the E_g for the unimplanted sample was high enough and did not appreciably change up to ~ 500 nm indicating that the PA spectrum depends on the optical spectrum (1-R), where R is the optical reflection spectrum for the unimplanted InP [11]. However, all PA spectra of the implanted InP did not so much depend on the optical spectra (1-R). The PA signal intensity decreased substantially even after the low-energy implantation and decreased successively with increasing implantation energy.

In order to catch a large PA signal, the heat generation by light absorption, the thermal conduction, the heat-to-elastic wave conversion, the propagation of elastic wave in a material should be sufficient [1].

Zammit [12] has reported that the value of thermal conductivity for ion implanted semiconductors is more than two orders of magnitude lower than the ones for the crystalline material and the values of the optical absorption coefficient of ion implanted semiconductors is more than one order of magnitude higher than the ones for the crystalline material.

The increase in the optical reflectivity with the ion-implantation in InP was less than 10 % [13]. This result suggests that the increase in the optical reflectivity has little effect on the decrease in the PA intensity.

Therefore, the successive decrease in the PA intensities with the increase in the implantation energy is considered to be mainly due to the increase in the thickness of the amorphous layers.

All of the spectra for the implanted samples had a maximum intensity near the E_g and had a long decreasing tail towards the shorter

Figure 2 The isochronal annealing curves of the PA signal intensity at the wavelength of 500 nm for Si⁺-implanted InP with implantation energy as a parameter.

wavelength side in the upper band-edge region. The tailing is interpreted to be caused predominantly by the wavelength dependence of the PA signal intensity following the wavelength dependence of the optical penetration depth (which is defined as the reciprocal of the optical absorption coefficient) within the implanted layers where strong optical absorption takes place [8].

As the decreasing tendency of the tails was monotonous and no remarkable structure was observed on the tails in Fig. 1, we can adopt PA signal intensity at any wavelength within the tails as a measure of implantation-produced damage. Consequently, we have employed the PA signal intensity at the wavelength of 500 nm as a measure of produced damage and have investigated the annealing behavior of the implanted layers.

Figure 2 shows the isochronal RTA curves of the PA signal intensity at the wavelength of 500 nm for the InP implanted with Si⁺ ions at energies of 35, 50, 100, 200 and 300 keV, respectively. It is noticed that these annealing curves are apparently affected by the implantation energies: the annealing curve for the sample implanted at a low energy of 35 keV had two peaks at 400 and 500 °C, the annealing curves for the samples implanted at a middle energies of 50, 100 and 200 keV had two peaks at ~ 500 and 650 °C and the annealing curve for the sample implanted at a high energy of 300 keV had only one peak at 650 °C.

Figure 3 shows the relation between the depth of the amorphous/crystalline (a/c) interface in InP implanted with Si⁺ ions at energies of 35, 50, 100, 200 and 300 keV, respectively and the optical penetration depth at the wavelength of 500, 600, 700 and 800 nm, respectively. The depth profiles of Si concentration after ion

implantation in Fig. 3-(a) were simulated by the LSS theory [14]. The implanted layers become amorphous by the heavy implantation and an interface generates simultaneously between the amorphous layers and crystalline substrate [2-4]. Moreover, another interface generates between a surface polycrystalline layers and the amorphous layers when the implantation energy is very high [4]. In Fig. 3-(a), the a/c interface is shown by the line (---) for all of the samples and the polycrystalline/amorphous (p/a) interface is shown by the line (....) for the sample implanted with Si⁺ ions at an energy of 300 keV. From the result in the previous works [2-4], the depth of the a/c interface in the InP implanted with Si⁺ ions at energies of 35, 50, 100, 200 and 300 keV were approximately estimated as 60, 80, 150, 310 and 450 nm, respectively and the p/a interface in InP implanted with Si⁺ ions at an energy of 300 keV was approximately estimated as 80 nm.

The optical penetration depth l is given by

$$l = 1/\alpha = \lambda / 4 \pi k$$

where α is the optical absorption coefficient, λ is the wavelength of light and k is the extinction coefficient. By using the extinction coefficient reported by Cardona [15], the l at the wavelength of 500, 600, 700 and 800 nm were approximately calculated as 82, 141, 330 and 470 nm, respectively. However, the l at the

Figure 3 The relationship between the profile of amorphous layers with implantation energy as a parameter and the optical penetration depth.

wavelength of 500 nm for the implanted InP is approximately 30 nm [16, 17].

On the other hand, the thermal diffusion length μ is given by [18]

$$\mu = (2k / \rho C \omega)^{1/2}$$

where k is the thermal conductivity, ρ is the density, C is the specific heat and ω is the angular modulation frequency of the incident light. By using physical parameters for InP at room temperature [19-22], μ is estimated as $\sim 190 \mu\text{m}$ for the 350 Hz modulation. Taking account that μ for the amorphous layers is more than two orders of magnitude lower than the ones for the unimplanted sample [12], the value of μ for the amorphous layers is estimated as less than $19 \mu\text{m}$. Therefore, the thermal conduction may be suppressed within a local region in the amorphous layers.

Figure 4 and 5 show the isochronal RTA curves of the PA signal intensity for the InP implanted with 35 and 300 keV Si⁺ ions with the wavelength as a parameter, respectively. Two remarkable peaks can be seen at 400 and ~ 550 °C on the annealing curves in Fig. 4 and they are tentatively named as P400 and P550, respectively. Moreover, the other two peaks can be seen at 450 and 650 °C on the annealing curves in Fig. 5 and also named as P450 and P650, respectively.

P400 in Fig. 4 suggests that the implanted layers transform from the amorphous state to the polycrystalline state as discussed in Ref. [5, 22] and simultaneously complicated defects are compiled near the a/c interface after annealing. The drastic decrease in the PA signal intensity at 400-450 °C suggests that the complicated defects

Figure 4 The isochronal annealing curves of the PA signal intensity for InP implanted with Si⁺ ions at an energy of 35 keV with the wavelength as a parameter.

Figure 5 The isochronal annealing curves of the PA signal intensity for InP implanted with Si^+ ions at an energy of 300 keV with the wavelength as a parameter.

decreased and solid phase epitaxial growth occurred from the substrate side. We consider that P550 in Fig. 4 indicates that the implanted layers transform from the polycrystalline state to the monocrystalline state.

P450 in Fig. 5 suggests that the implanted layers transform from the amorphous state to the polycrystalline state as discussed in the Ref. [2,9]. The light does not reach the a/c interface as shown in Fig. 3. Therefore, we have interpreted that P650 in Fig. 5 is due to the compiling of the complicated defects near the p/a interface after annealing. Thus, the drastic decrease in the PA signal intensity at 650-700 °C suggests that the complicated defects decrease in the polycrystalline state.

4. CONCLUSIONS

The annealing behavior of the amorphous layers produced by heavy Si^+ implantation in InP substrates was studied using the piezoelectric PAS with implantation energy as a parameter. The usefulness of PAS was elucidated for investigating depth profile of disorder (defects) in implanted layers and its annealing characteristics. We found that annealing behavior of PA signal intensity depended on the thickness of the amorphous layers and the light penetration depth in the sample.

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