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Ion-Beam Synthesis of InAs Nanocrystals in Crystalline Silicon

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Abstract—The formation of nanodimensional InAs crystallites on Si wafers was studied by the method of high-fluence implantation of As and In ions with subsequent high-temperature treatment. It was found that the size and depth distributions of the crystallites depend on both the implantation temperature and the annealing conditions. A broad band in an energy range of 0.75–1.1 eV was recorded in the photoluminescence spectra of the samples.

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INTRODUCTION

The synthesis of direct-gap semiconductors A^3B^5 in a Si matrix is of interest in designing the next generation of photodetectors and light-emitting diodes based in silicon technology. We earlier reported we had obtained coherent InAs nanocrystals in Si (001) by the hot high-fluence implantation of As and In ions with subsequent annealing [1]. In this work, we present the results from studying the effect of the implantation and annealing regimes on the processes of the ion-beam synthesis of InAs nanocrystals in silicon.

EXPERIMENTAL

Silicon wafers were first implanted with As ions (245 keV, 4.1×10^{16} cm^{-2}) and then with In ions (350 keV, 3.7×10^{16} cm^{-2}) at 25 and 500°C. Part of the samples implanted with heavy ions at room temperature were additionally exposed to H_2^+ ions with an energy of 100 keV and a fluence of 1.2×10^{16} cm^{-2} in terms of atomic hydrogen. This procedure was performed to obtain an internal getter at a depth about of 500 nm during post-implantation annealing. The samples were subsequently annealed in an inert ambient (900°C, 60 min). The fluences of hot ion implantation were reduced by a factor of 1.5 and the annealing duration was increased (from 30–45 to 60 min) as compared to the experiment described in [1]. To analyze the depth distributions of the implanted impurities and to study the structural and optical properties of the samples, we applied the methods of Rutherford backscattering (RBS), transmission electronic microscopy (TEM), and photoluminescence (PL).

RESULTS AND DISCUSSION

Figure 1 presents the RBS spectra of the samples under study. Analysis of the spectra shows that implantation at room temperature results in the formation of an amorphous layer with a thickness of 330–350 nm. Subsequent annealing leads to a restoration of the crystal structure and to a significant redistribution of impurities. An significant decrease in the amount of implanted impurity is observed; in addition, about half the arsenic atoms are in lattice sites. After heat treatment, the random spectra of samples with and without a getter coincide. In the aligned spectrum of a sample with a getter, however, in the channel range from 150 to 220, the yield of backscattered He^+ ions is less (by 10%) than in a sample without a getter. In the case of hot implantation, no amorphization of the near-surface region is observed. In our opinion, the increase in the yield of backscattered He^+ ions in the aligned spectrum (spectra from 170 to 190) corresponds to a region of imperfections located deeper in the sample (as compared to the impurity maximum). The incorporation of part of the impurities into the silicon lattice sites is observed immediately after hot implantation. High-temperature annealing of the given samples leads to further significant restoration of the silicon matrix's crystal structure, and to the incorporation of approximately half of the implanted impurities into the silicon matrix sites.

Figure 2 shows the depth profiles of In and As in silicon samples simulated (SRIM'2003) and calculated from the experimental RBS spectra. The calculation of As and In concentrations in Si by RBS spectra is complicated by the overlapping of peaks from In and As. To solve this problem, we measured RBS spec-

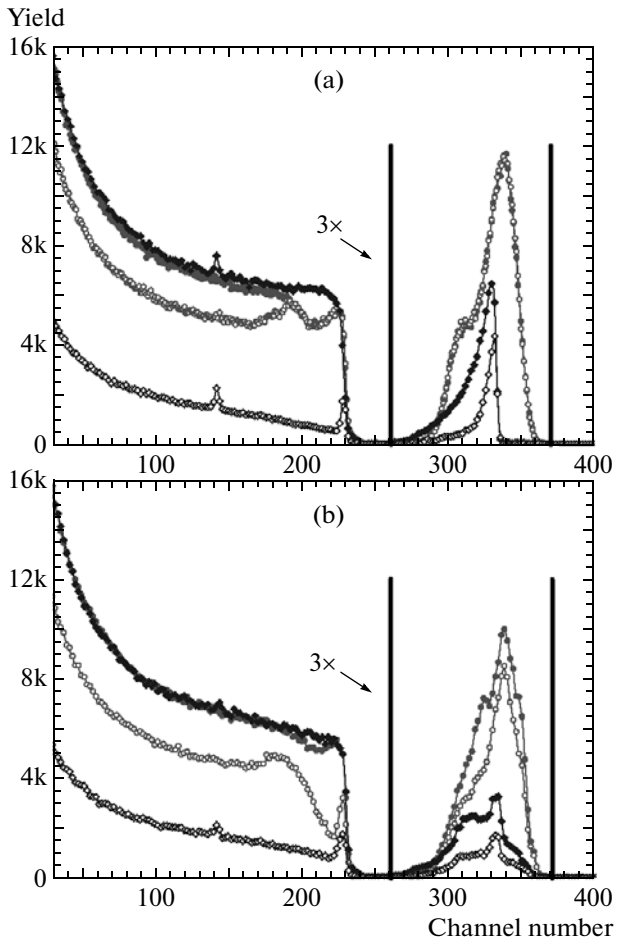

Fig. 1. RBS spectra of Si samples implanted with As ions (245 keV, 4.1×10^{16} cm^{-2}) and In ions (350 keV, 3.7×10^{16} cm^{-2}) at temperatures of 25 (a) and 500°C (b) and annealed at 900°C for 60 min. Random spectra are depicted by open circles; spectra upon channeling, by full circles.

tra at two angles of the incidence of helium ions into the samples: 0° and 50°. The depth profiles were calculated by simulations of the spectra until they coincided completely with the experimental spectra obtained at two angles of the incidence of helium ions into the samples. The profiles of In and As after implantation at room temperature are close to the calculated profiles. The hot conditions of implantation lead to a broadening of the depth profiles as compared to the calculation data, and a displacement of the depth profiles toward the sample surface is observed. The subsequent high-temperature annealing of the implanted samples (for the two implantation temperatures) results in a significant redistribution of impurity atoms and a decrease in its concentration. Finally, (after heat treatment), hot implantation leads to broader (up to 400 nm deep) depth profiles as compared to implantation at 25°C.

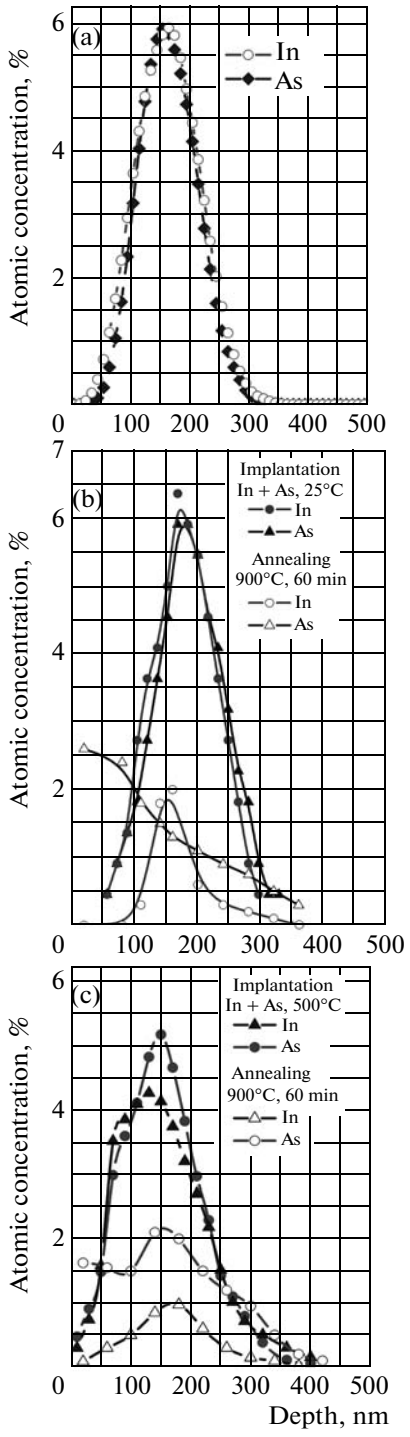

Fig. 2. Simulated (SRIM 2003) (a) and calculated (RBS spectra) depth profiles of As and In atoms in silicon implanted at 25 (b) and 500°C (c).

The results of the TEM studies are depicted in Fig. 3. For the sample implanted at room temperature with an additional implantation of hydrogen, a thin layer of secondary defects (mostly dislocation loops) is registered at a depth of approximately 500 nm. The

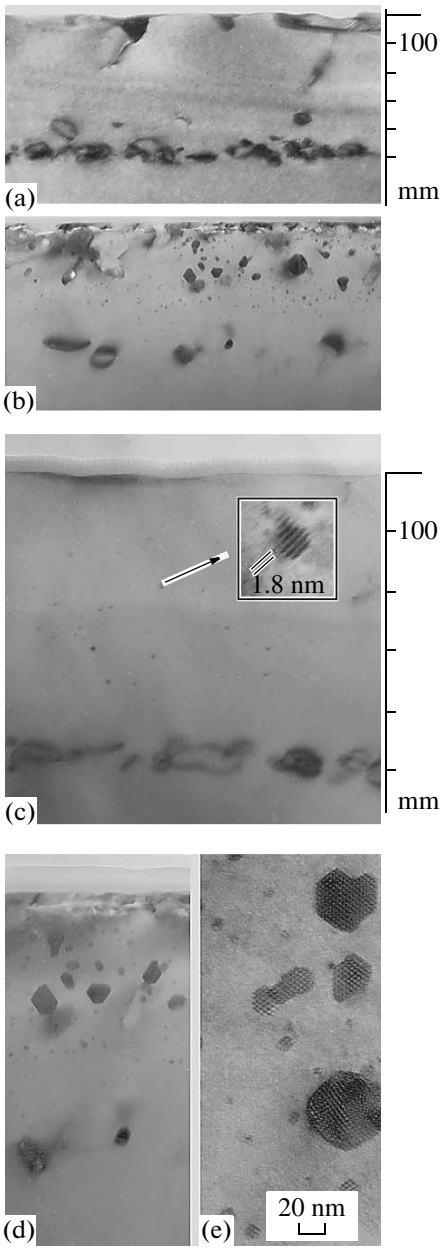

Fig. 3. TEM images of the cross-section of silicon samples after implantation of In and As ions at 25 (a, c) and 500°C (b, d, e) and high-temperature annealing.

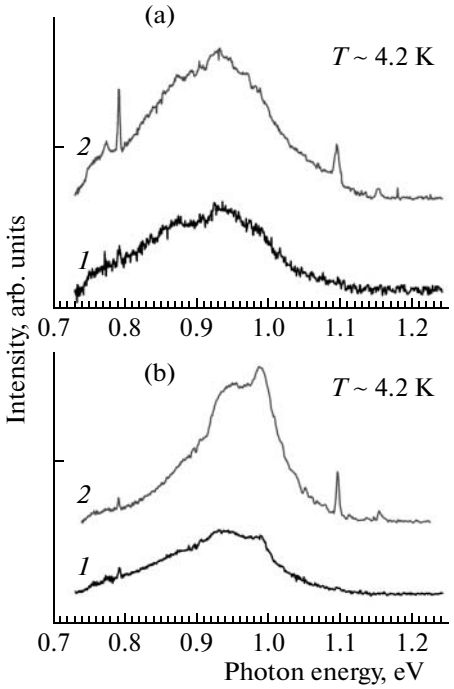

Fig. 4. PL spectra of silicon samples after implantation of As^+ and In^+ ions at 25 (a) and 500°C (b) and high-temperature treatment.

formation of defects of this sort is characteristic of the process of recrystallization of amorphous layers. Separate inclined dislocations are observed throughout the entire implanted layer. The irregularity (roughness) of the surface in comparison with the initial wafer should be noted. This presumably may be attributed to defect system transformation during annealing and to a shift of impurities (indium) from the near-surface region. At depths from 100 to 350 nm, there are small precipitates from 2 to 10 nm in size. This region in the crystal corresponds to concentration maxima in the implanted impurity profiles. A detailed study of the structure of these inclusions according to the technique described in [1] allowed us to identify them as InAs nanocrystals. In the case of hot implantation, two spatially separated layers of secondary defects are observed. The first defect layer containing micropores and microtwins is localized in the thin near-surface region. In the deeper defect layer (400–450 nm), separate dislocation loops are recorded. The density of secondary defects is significantly lower than for the samples described in [1]. Between the two defect layers, at the sample depth of 80–350 nm, there is a defect-free silicon region containing InAs precipitates. Alongside the small clusters (from 2 nm), considerably larger ones with sizes up to 80 nm are observed (Fig. 3e). Increasing the duration of heat treatment up to 60 min thus leads to a reduction in the density of secondary defects in the structure and to an appreciable increase in the size of InAs precipitates (in [1], the average size of precipitates was 3–6 nm for an annealing duration of 45 min).

Figure 4 depicts the PL spectra of samples measured at 4.2 K after implantation and subsequent annealing. For the crystals implanted at 25°C, a broad band in a range of 0.75–1.1 eV with a maximum of 0.93 eV is recorded in PH spectra. The intensity of this band is almost five times greater for the samples with a getter layer in comparison with the sample without getter (curves *2* and *1* in Fig. 4a, respectively). A band with a phononless line of 0.79 eV is observed in the spectrum, due to the recombination of bound excitons

on ion-induced defects (interstitial carbon–interstitial oxygen (C_i–O_i pairs)) [2]. For the samples implanted at 500°C, a broad band in the range 0.75–1.1 eV with an extended low-energy wing is also found in the PL spectra (curve *1* in Fig. 4b). The intensity of this band is four times greater than that of samples implanted at room temperature (Fig. 4a, curve *1*). For purposes of comparison, Fig. 4b depicts the PL spectrum of a sample for which the implantation fluences of arsenic and indium ions were higher by a factor of 1.5 and the duration of annealing at 900°C was less (curve *2*) as compared to the conditions of the present experiment [1]. We may assume from a comparison of the spectra in Fig. 4b that the broad band in a range 0.75–1.1 eV is a superposition of at least two PL bands with maxima of ~0.94 and ~0.99 eV.

CONCLUSIONS

In this work, we studied the influence of impurity (As + In) implantation temperature and regimes of post-implantation annealing on the processes of the ion-beam synthesis of InAs nanocrystals in silicon. It was found that a decrease in the fluence of ions and a reduction in the duration of heat treatment allow us to reduce the level of damage in an implanted layer. An increase in the duration of annealing, however, leads also to an increase in the size of formed InAs nanocrystals (up to 80 nm). For all of the samples, the PL spectra exhibit a broad band in the spectral range 0.75–1.1 eV. Application of an additional implantation of hydrogen ions for the formation of a gettering layer in the process of post-implantation annealing makes it possible to significantly increase the intensity of the given PL band.

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