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PHYSICS OF SEMICONDUCTOR DEVICES

Formation of Donor Centers upon the Annealing of Silicon Light-Emitting Structures Implanted with Oxygen Ions

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Abstract—It is found that the implantation of silicon with oxygen ions and subsequent annealing at high temperatures are accompanied by the formation of electrically active donor centers and by the *p*–*n* conversion of the conductivity of silicon. The concentration and spatial distribution of these centers depend on the annealing temperature. The results are accounted for by the interaction of oxygen atoms with intrinsic point defects formed upon the annealing of implantation damages.

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1. INTRODUCTION

At present, extensive studies aimed at the development of light-emitting structures for silicon optoelectronics are being carried out [1]. It has been found that donor centers are formed upon the fabrication of silicon light-emitting structures by the implantation of Er ions and subsequent annealing [2–4]. In these cases, the concentration of the donor centers being formed frequently exceeds the concentration of acceptor centers in the initial crystals and $p \longrightarrow n$ conversion of the conductivity of the silicon layer occurs. The influence exerted by implantation, temperature, time, and annealing medium on this effect has been studied. The characteristic properties of samples of this kind were the introduction rate and concentration of thermal donors formed (~10^{17} cm^{-3} in a characteristic time of ~30 min at temperatures of ~700°C). Another distinctive feature of these thermal donors was the comparatively high temperature (~1000°C) at which they survive, in contrast to classical oxygen thermal donors. Measurements of the current–voltage characteristics in structures of this kind have shown that the concentration profiles of electrons in the *n*-type layer have the form of curves with a maximum, with the concentration at the maximum becoming lower as the temperature is increased [5]. Hall-effect measurements performed in a wide temperature range with samples implanted with erbium ions have revealed that three groups of energy levels are formed in the lower half of the energy gap of silicon, with ionization energies of ~0.02, ~0.15, and ~0.38 eV [6]. It has been demonstrated that shallow thermal donors are formed from oxygen atoms and intrinsic point defects (IPD), whereas two other groups include oxygen atoms and rare-earth ions. A similar pattern in which three families of thermal donors were formed with somewhat different energy levels has been observed in the implantation of other rare-earth ions: Dy, Ho, and Yb into silicon, followed by high-temperature annealing [7]. Recently, intensive studies have been carried out in order to develop light-emitting structures with so-called dislocation luminescence by, in particular, the implantation of silicon [1, 8] or oxygen ions [1, 9]. In the present study, we examine the possibility of the formation of thermal donors by the implantation of oxygen ions and subsequent annealing to produce light-emitting structures with dislocation luminescence.

2. EXPERIMENTAL

As substrates served Cz-*p*-Si:B ⟨100⟩ wafers with a thickness of 300 μm, diameter of 100 mm, and resistivity of 12 Ω cm (KDB-12 brand). Measurements of IR (infrared) absorption in the initial sample demonstrated that the concentration of oxygen was ~10^{18} cm^{-3} and that carbon was below the detection limit of 2×10^{16} cm^{-3}. To obtain a uniform distribution profile of the oxygen impurity, the ions were implanted with three different energies and doses: $350/1.5 \times 10^{15} + 225/0.9 \times 10^{15} + 150/0.7 \times 10^{15}$ keV/cm^{-2}. The projected ranges of ions were 0.34, 0.49, and 0.71 μm, respectively [10]. Implantation was performed on a High Voltage Engineering Europe implanter (The Netherlands). To preclude channeling, the substrate was turned 7° relative to the ion beam. According to calculation by SRIM software [10], the concentration of oxygen at a depth of 0.42 to 0.63 μm was constant at a level of ~6×10^{19} cm^{-3}. The full width at half-maxi-

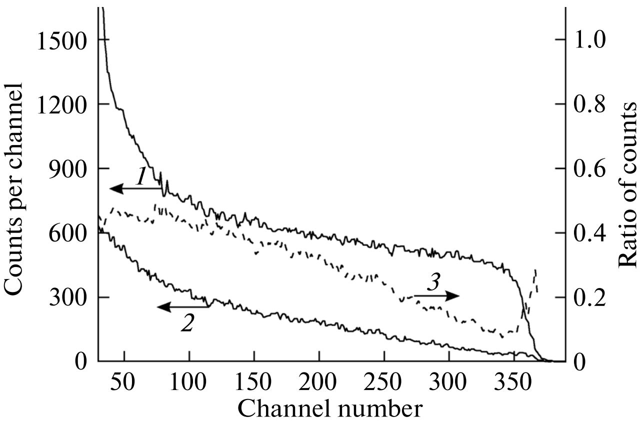

Fig. 1. RBS proton spectra measured in (*1*) the random and (*2*) channeling modes and (*3*) the ratio between the amplitudes of the channeling and random RBS signals for an implanted Cz-*p*-Si:O sample.

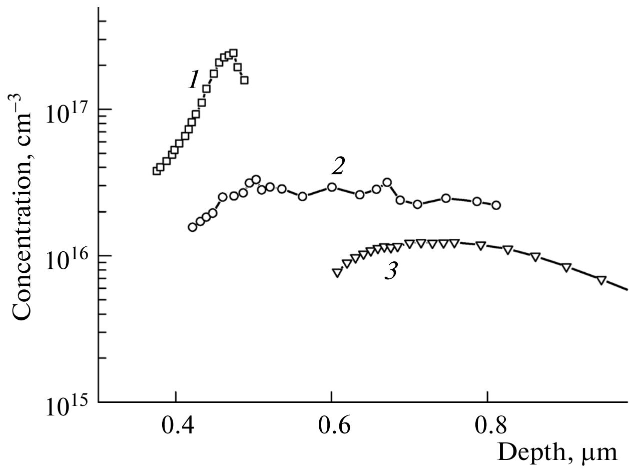

Fig. 2. Electron-concentration profiles in the *n*-type layer of silicon upon its implantation with oxygen ions and annealing for 0.5 h at different temperatures: (*1*) 700, (*2*) 900, and (*3*) 1000°C.

mum of the oxygen distribution was in the range 0.26–0.85 μm. The Rutherford backscattering (RBS) spectra, measured with 227-keV protons in the random and channeling modes in a sample upon the implantation of O ions, are shown in Fig. 1 (curves *1* and *2*, respectively). Analysis of the spectra shows that the implanted layer is not amorphized: the degree of amorphization, characterized by the ratio of the intensities measured in the channeling and random modes (curve *3*), is substantially smaller than unity. Calculation of the concentration profile of point defects, normalized to the concentration of atoms in the Si lattice, from the RBS spectrum demonstrated that the maximum radiation-damage level attains a value of 16%.

Isochronous (over 30 min) annealing of the implanted samples was performed at temperatures of 700, 900, and 1000°C in a chlorine-containing atmosphere. This atmosphere had the form of an oxygen flow saturated with a carbon tetrachloride vapor at a concentration of 1 mol %. The conductivity type of the surface layer was monitored with a thermal probe. The carrier concentration profiles were found from the capacitance–voltage characteristics of a Hg–Si Schottky barrier (mercury probe) at room temperature and probe signal frequency of 1 MHz.

3. RESULTS AND DISCUSSION

The measurements performed with the thermal probe demonstrated that the implantation of oxygen ions and subsequent annealing resulted in the formation of an *n*-type layer in the surface region, i.e., the $p \longrightarrow n$ conversion of the conductivity type of silicon was observed. The experimental electron-concentration profiles are shown in Fig. 2. The concentration profiles have the form of curves with maxima. As the annealing temperature is raised, the concentration at the maximum decreases from 2.2×10^{17} cm^{-3} (for annealing at 700°C) to 1.2×10^{16} cm^{-3} (for annealing at 1000°C). As the isochronous-annealing temperature increases, the depth at which the maxima $n(x)$ lie increases from 0.47 μm at 700°C to 0.73 μm at 1000°C.

It is of interest to note that the donor-center profiles shown in Fig. 2 are nearly the same and close to the donor-center profiles in silicon samples implanted with erbium ions and annealed in similar temperature-and-time modes in [5] (Fig. 1, curves *2–4*). This suggests, by analogy with [5], that the donor centers are formed by oxygen atoms, with IPDs involved. At low annealing temperatures, the concentration of the donor centers being formed is the highest. As the annealing temperature is increased, with an increasingly large part of implantation distortions annealed, the concentration of point defects decreases and their mobilities grow, with the concentration of donor centers decreasing as a result. In the process, the position in which the donor concentration is the highest becomes farther from the surface because nonequilibrium intrinsic point defects move away toward the surface. With the temperature raised further, the increasing part of these defects has enough time to reach the drains. As a result, the maximum donor concentration decreases and the maximum is shifted depthward. The position of the donor centers being formed almost coincides with the region in which the majority of structural defects, and primarily oxygen precipitates and dislocation loops, were formed [1]. This serves as one more indication that oxygen atoms and intrinsic point defects in the silicon lattice are involved in the formation of donor centers. The involvement of oxygen atoms in the formation of donor centers is also supported by the results obtained in the study [11] in which the additional implantation of oxygen ions and annealing at 700°C yielded so-called thermal double oxygen donors.

Thus, it was found that intrinsic point defects are involved, in addition to oxygen atoms, in the formation of donor centers upon the annealing of silicon implanted with oxygen ions. Comparison of the results obtained in the study of the luminescence, structural, and electrical properties of silicon implanted with oxygen ions during the course of annealing unambiguously indicates that the processes in which structural defects and luminescent and electrically active centers are transformed should be regarded as a single unit.

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