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Residual defects in low-dose arsenic-implanted silicon after high-temperature annealing

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ABSTRACT

We investigated the residual defects in low-dose (10^{13} cm^{-2}) arsenic implanted Si after high-temperature (1100 °C) annealing. The presence of residual damage was successfully revealed after using a rapid thermal process for heat treatment. This damage was identified as vacancy-type defects distributed near the surface, such as tetravacancies or pentavacancies. When O_2 gas was introduced to the annealing chamber, vacancy-type defects were transformed into divacancy and carbon–oxygen complex. They were confirmed to be created by a non-equilibrium reaction during the rapid cooling-down step in the annealing sequence.

1. Introduction

Impurity implantation is an essential process for manufacturing silicon (Si) devices. Since the accelerated ions introduce lattice damage during implantation, subsequent annealing must be applied to heal the damage as well as to activate the impurities. If the implant damage is not eliminated, it may cause degradation of the device's performance. Therefore, residual damage that persists after annealing is a matter of growing concern in the Si semiconductor industry [1].

One example is end-of-range (EOR) defects. If the implant dose is higher than the critical dose of amorphization (10^{14}–10^{16} cm^{-2}), dislocation loops can be created even after annealing beyond the amorphous/crystalline interface. These defects have been evaluated by transmission electron microscopy (TEM) [2,3] and Rutherford backscattering spectrometry (RBS) since 1960's [4,5]. They have been confirmed to lead to the fatal problem of junction leakage and/or transient enhanced diffusion (TED) [6,7]. In contrast, even under low-dose implant conditions that are below the critical dose (<10^{13} cm^{-2}), point defects are known to remain when the annealing temperature is relatively low (<700 °C). These defects have been investigated using optical and electrical characterization methods such as electron spin resonance (ESR) [8,9], infrared absorption spectroscopy (IR) [10,11], photoluminescence (PL) [12,13] and deep transient level spectroscopy (DLTS) [14,15]. For the last 50 years, numerous studies have been carried out on these defects and their annealing behavior under low-dose implant conditions. However, there are few reports on defects that develop after applying high-temperature (>1000 °C) annealing: they have not been directly characterized in low-dose implanted and high-temperature annealed Si [16,17]. The conventional view is that no damage remains under these conditions, but that if it does exist, it has minimal influence on device performance. Little attention has thus been paid to defects that might remain after low-dose implantation processes.

In a previous study, we showed the presence of residual damage in low-dose (10^{13} cm^{-2}) arsenic (As) implanted Si after high-temperature (>1000 °C) annealing when using rapid thermal processes for heat treatment [18]. The characterization technique we used was a cathodoluminescence (CL) method [19,20]. Applying the CL technique to Si materials has been restricted because of its low luminescence efficiency. However, we have shown this technique, when used to compare luminescent intensity, to be an efficient tool for characterizing a various kinds of defects and/or crystal disorders. CL analysis clearly revealed that non-radiative decay centers are present in the crystal [18].

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We undertook this study to clarify the details of the damage. We prepared low-dose (10^{13} cm^{-2}) As implanted Si and subjected it to rapid thermal annealing (RTA) at a high temperature (1100 °C). We also introduced oxygen (O_2) to the annealing chamber in addition to nitrogen (N_2). We evaluated the residual damage using positron annihilation spectroscopy (PAS) in addition to the CL method. The defects and their evolution during annealing were investigated by comparison with carrier properties obtained by sheet resistance measurements.

2. Experimental

Fig. 1 shows the process of making of the samples used in this investigation. The base material was a p-type Cz-Si wafer with (100) orientation. After a 10 nm-thick thermal oxide layer was grown, As^+ ions were implanted at normal incidence angle through the oxide layer at 150 keV to a dose of 1.0×10^{13} cm^{-2}. The samples were annealed at a top temperature of 1100 °C for 50 s using a hot-wall type RTA system. The heating rate and cooling rate were set at 40 and 80 °C/s respectively. Nitrogen (N_2) and oxygen (O_2) mixed gas was introduced to the annealing chamber at various O_2 concentrations (0%, 5%, 10%, 20% and 30%). An oxide-layer-only grown sample was prepared as reference, and an as-implanted sample was also prepared for comparison.

For cathodoluminescence (CL) measurements, a Hitachi S-4300SE scanning electron microscope (SEM) with a Schottky emission-type gun was used as the excitation source. The acceleration voltage of the electron beam was 15 kV. The emitted luminescence was collected using an ellipsoidal mirror and optical fiber, and analyzed using a Jobin Yvon HR-320 single monochromator equipped with an InGaAs multichannel detector. All CL measurements were performed at 30 K. The details of the CL measurement system are described elsewhere [21,22].

The sheet resistance was measured using a Frontier Semiconductor RsL300, a non-contact photo-voltage based sheet resistance and leakage current mapping tool [23]. The wavelength and Rs frequency of the modulated LED were 700 nm and 100 kHz. The 1000 iterated measurements of each point improved repeatability by up to 0.08% [23].

Before positron annihilation spectroscopy (PAS) analysis, the oxide layers were removed with hydrofluoric (HF) acid. The Doppler broadening spectra of the positron annihilation radiation were measured with a Ge detector as a function of the incident positron energy. The low-momentum part of the spectra was characterized using the S parameter, which was defined as the number of annihilation events over the energy range of 511 keV ± ΔE (where ΔE = 0.76 keV). This S parameter is an index of the amount and size of vacancy-type defects [24]. The relationship between S and E was analyzed using VEPFIT, a computer program developed by van Veen et al. [25]. The depth distributions of the S parameter were obtained by fitting the S–E curve. The W parameter, defined as the number of annihilation events in the range of 3.4 keV $\leqslant \Delta E \leqslant$ 6.8 keV, was also obtained to examine the annihilation characteristics in detail. The lifetime spectra of positrons were measured using a pulsed monoenergetic positron beam [26]. The incident positron energy was fixed at 1 keV. The positron lifetime and its intensity of the ith component, τ_i and I_i, are given by analyzing the lifetime spectra using a computer program called RESOLUTION [27]. The details of the PAS measurement system are described elsewhere [28,29].

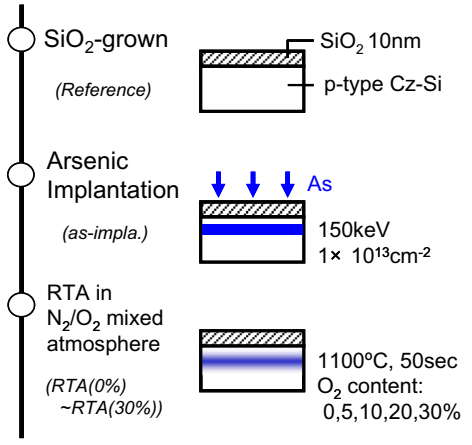

Fig. 1. Fabrication of the samples used in this investigation.

3. Results and discussion

Fig. 2 shows the CL spectra of all the samples. Two emission lines, labeled TO and TO + O^{Γ}, can be observed in the spectrum of the reference sample. These lines are typical band-to-band transitions followed by the emission of transverse optical (TO) phonons and optical phonons at $k = 0$ (O^{Γ}) [30]. No peaks can be seen other than the TO and TO + O^{Γ}-lines. It can thus be concluded that the defect density is low just after the oxide layer has grown. In contrast, the intensity of the TO-line is reduced after As implantation. A W-line, C-line and broad band in the long-wavelength region are detected in the spectrum of the as-implanted sample. The W-line emission is considered to originate from Si self-interstitial clusters [30–33]. The C-line is well recognized as the emission from the interstitial carbon and interstitial oxygen (C_i–O_i) complex [30,34–36]. The origin of the broad band is not clear. It might be due to certain point defects or their complexes being broadened by an inhomogeneous disorder in the lattice. These defect-related lines reflect the development of implant damage caused by the impact of accelerated As ions. When this implanted sample was

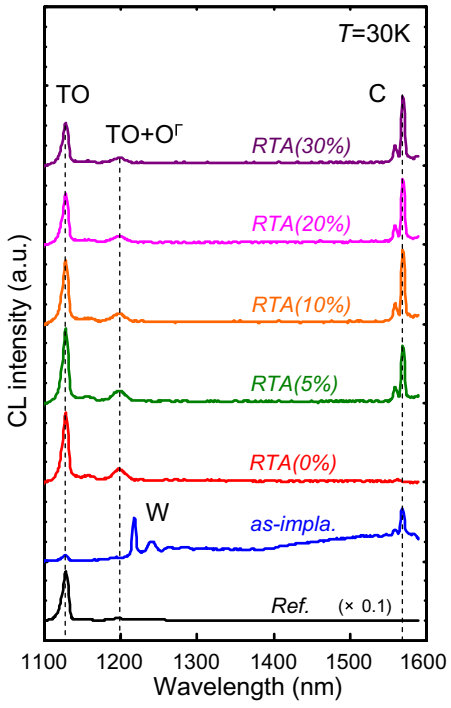

Fig. 2. CL spectra of reference, as-implanted and RTA-applied samples with various proportion of O_2 concentration in the annealing atmosphere (0%, 5%, 10%, 20% and 30%).