STUDYING THE PROPERTIES OF GADOLINIUM-DOPED SILICON

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The behavior of gadolinium atoms in silicon was studied and it was found that diffusion doping of n-Si with gadolinium leads to a sharp increase in the resistivity. This indicates that gadolinium introduces acceptor centers in silicon. A decrease in the concentration of optically active oxygen by 10 ± 30% was found in comparison with heat-treated control samples.

**Abstract.** The behavior of gadolinium atoms in silicon was studied and it was found that diffusion doping of n-Si with gadolinium leads to a sharp increase in the resistivity. This indicates that gadolinium introduces acceptor centers in silicon. A decrease in the concentration of optically active oxygen by 10 ± 30% was found in comparison with heat-treated control samples.

**Keywords:** silicon, rare earth element, gadolinium, diffusion resistivity, oxygen, carbon

It is known that the doping of silicon with rare earth elements significantly affects the performance of semiconductor devices and integrated circuits [1-3]. In addition, there are conflicting data in the literature on the electrical activity of REE atoms and their interaction with other defects. Most works lack information on the electrical activity of REE atoms. It is known that REEs introduced into silicon from a melt during growth, possessing high chemical activity, are present in silicon in an electrically inactive state [4-5].

Therefore, the aim of this work was to comprehensively study the behavior of Gd atoms in silicon and their interaction with growth impurities. Si was doped with gadolinium by the diffusion method in vacuum from a deposited layer of high purity Gd (99.999%). Diffusion was carried out at 900 - 1250°C for 2-100 hours. For doping, n-Si was used with an initial resistivity from 1 to 100 Ohm cm and p-Si from 1 to 100 Ohm cm. After diffusion in the samples in Si<<Gd>>, their resistivity was measured by the four-probe method and compared with the initial values for the samples both n- and p- types.

The introduction of Gd into Si at T_d=900-1000°C almost does not change the resistivity of n-Si and p-Si. In n-Si crystals after diffusion of gadolinium at T>1100°C ρ increased, while in p-Si the value of ρ slightly decreased.

The results of measurements of ρ after diffusion of Gd in Si at 1200°C for 50 hours are presented in the table.

**Table 1. Specific resistance of control and doped samples of the n-Si <Gd> and p-Si <Gd> types**

<table>
<thead>
<tr>
<th>Samples</th>
<th>№</th>
<th>ρ samples Si&lt;&lt;Gd&gt;&gt;</th>
<th>ρ, control samples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>KDB-15</td>
<td>1</td>
<td>14,6</td>
<td>14,7</td>
</tr>
<tr>
<td>KDB-15</td>
<td>2</td>
<td>15,2</td>
<td>14,9</td>
</tr>
</tbody>
</table>
The measurements were carried out on several batches of samples with different initial resistivity $\rho_{\text{res}}$. As can be seen from the table, in all n-type Si samples after doping with gadolinium, a change in the conductivity type and a sharp increase in the resistivity are observed. In p-type Si samples, the resistivity values slightly decrease, but the conductivity type remains unchanged. The resistivity of the control samples that underwent a similar heat treatment remained almost unchanged.

From the change in the values of the resistivity $\rho$ of Si samples after doping with Gd atoms, it can be concluded that gadolinium introduces acceptor centers in silicon.

On samples of silicon, diffusion-doped with gadolinium, and also subjected to control heat treatment, measurements of the profile of resistivity in depth were carried out. Analysis of the results showed that the distribution profile in Si $\langle\text{Gd}\rangle$ samples is not described by the erfc function, but consists of two sections: first, there is a sharp increase in the resistivity to a depth of 50 μm, then the resistivity value stabilizes and no noticeable change in the resistivity with depth is observed.

A similar profile of the resistivity distribution was observed for transition metals in silicon, such as nickel, manganese, etc. [6]. The first, near-surface region, is characterized by a sharp increase in by 4-5 orders of magnitude, and the second - by an almost uniform distribution of $\rho$ in the volume of silicon. It should be noted that the values of $\rho$ in the control samples (without REE impurities) do not change noticeably with depth.

In parallel, the IR absorption spectra were measured on samples of the same series. For studies, n-Si and p-Si grown by the Czochralski method with the concentration of optically active oxygen and carbon $N_{\text{overt}} = 6 \cdot 10^{17} \pm 1.2 \cdot 10^{18}$ cm$^{-3}$ and $N_{\text{c overt}} = 2 \cdot 10^{16}$ cm$^{-3}$ were used as the initial samples, respectively. The resistivity of the original samples was from 1 Ohm·cm to 100 Ohm·cm, the thickness of the polished samples, depending on the task at hand, was 1-1.5 mm.

The content of oxygen $N_{\text{overt}}$ and carbon $N_{\text{c overt}}$ was estimated from the IR absorption spectra of 1100 cm$^{-1}$ (oxygen band) and 610 cm$^{-1}$ (carbon band), measured on a Specord-IR-75 infrared spectrophotometer in a two-beam scheme at 300 K.

As a control (reference) sample, we used polished oxygen-free silicon of the same thickness as the sample under study with $N_{\text{overt}} \leq 10^{16}$ cm$^{-3}$, $N_{\text{c overt}} = 5 \cdot 10^{15}$ cm$^{-3}$. After diffusion of gadolinium in the same samples, $N_{\text{overt}}$ and $N_{\text{c overt}}$ were measured by IR absorption. The results of these measurements showed that after the introduction of gadolinium in both n- and p-Si, a decrease in the concentration of optically active oxygen by 10-30% is observed in comparison with the control samples heat-treated under the same conditions as the diffusion of gadolinium.

Also, IR spectra were recorded at a wavelength $\lambda=16.4$ μm, corresponding to the absorption of optically active carbon in silicon. In the control and doped samples, the effect of reducing the optically active carbon was not observed.
Thus, it follows from the results obtained that the diffusion doping of n-Si with gadolinium leads to a sharp increase in the resistivity, which allows us to conclude that gadolinium introduces acceptor centers in silicon. Also, a decrease in the concentration of optically active oxygen by 10±30% was found in comparison with the heat-treated control samples.

References