Au²⁺-Implanted Regions in Silicon Visualized Using a Modulated Free-Carrier Absorption Method

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Received: 24 October 2016 / Accepted: 8 May 2017 / Published online: 18 May 2017
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Abstract Silicon samples were implanted with Au²⁺ ions of energy 100 keV and doses of 10¹⁴ cm⁻². The area of the implanted region was 2 mm × 2 mm. The size of the Si substrate samples was 5 mm × 5 mm × 0.4 mm. Spatial distributions of the amplitude and profiles of the modulated free-carrier absorption (MFCA) signal of the implanted silicon samples were recorded and analyzed. The data were obtained using an experimental setup built specifically for MFCA amplitude mapping and measurements of frequency characteristics. For example, the maps and profiles showed that for 520 nm laser illumination, the MFCA amplitude in the implanted region was considerably smaller than that for the substrate. The values of the amplitude of the MFCA signal from the implanted region depended on the wavelength of illuminating light. They convey information related to the optical absorption coefficient of the implanted layers.

Keywords Absorption coefficient · Ion-implanted silicon · Modulated free-carrier absorption · Nondestructive testing · Photothermal visualization

Selected papers from Third Conference on Photoacoustic and Photothermal Theory and Applications.

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1 Introduction

The implantation of silicon with high-energy ions at high doses causes huge structural changes. These changes result among others in the decrease in value of recombination parameters such as the lifetime of optically generated carriers, their diffusion coefficients, and the velocity of their surface recombination. The implantation causes the amorphization of the implanted region what also results in increases in the optical absorption coefficient spectrum. Photothermal radiometry (PTR) and the modulated free-carrier absorption (MFCA) method proved useful in investigations of thin implanted layers in semiconductors. The first investigations of implanted silicon samples employing PTR started in 1996 [1–4]. Spectral characteristics of the PTR signal obtained for a p-type silicon implanted with phosphor ions at different doses and energy of ions 150 keV were presented in paper [1]. In [2], similar results for n-type silicon implanted with phosphor of energy 50 keV and a dose 10^{13} cm^{-2} were presented. These results were extended to different doses (10^{10} to 10^{16} cm^{-2}) and energies 50 keV to 150 keV in [3] and to silicon samples implanted with boron in [4]. The common feature of these results was the decrease in the plasma component of the PTR signal observed for implanted samples in relation to non-implanted samples. The inference was that carrier lifetimes in the implanted layers decreased.

Results of investigations on the influence of Ar^{8+} - and O^{6+} -ion implantation in silicon on the PTR signal were presented in [5–7]. For Ar^{8+} -ion-implanted silicon, spectral characteristics of the PTR signal appear in [6] and for O^{6+} -ion-implanted silicon those can be found in [7]. The observed decrease in the plasma component of the PTR signal was interpreted as a result of not only a strong decrease in carrier lifetime in the implanted layer but also a strong increase in the optical absorption coefficient of the implanted layer.

The MFCA method used in the experiment involves the illumination of the sample with an intensity-modulated pumping beam of light of photon energy greater than the energy gap of the semiconductor and the subsequent measurement of the amplitude of modulation of the infrared (IR) beam passing through the sample. If a semiconductor sample is illuminated with modulated laser light, then plasma waves arise. The influence of these plasma waves on the photoacoustic signal has been described in [8–10]. The amplitude modulation of the IR beam of light is caused by the modulation of the concentration of carriers (i.e., the plasma waves) in the sample arising from beam absorption, specifically free carriers absorbing IR light.

The MFCA method, among others, was used to map the lifetime of carriers in the silicon wafers [11]. The experimental setup was first established and tested in measurements of lifetimes of carriers in non-implanted Si wafers [12]. This photocarrier radiometry was also employed in investigations of implanted semiconductor samples in approaches using two and three wavelengths of light [13, 14]. The former approach was applied to silicon implanted with B^+ , As^+ , P^+ ; the latter approach was applied to As^+ implanted silicon.

To the best of our knowledge, we present the first attempt of estimating the increase in value of the optical absorption coefficient of an ion-implanted region in silicon using the MFCA method.

Fig. 1 Schematic of the experimental setup used to map the implanted regions in silicon wafers

2 Experimental Setup

The experimental setup used for the measurements of the distribution and profiles of the amplitude of the MFCA signal is shown in Fig. 1.

For optical generation of carriers, four diode-laser beams of different wavelengths, 808 nm, 660 nm, 520 nm, and 480 nm were used. The wavelength of the IR beam was 1600 nm. The intensity of IR light was measured with a fast-response photodetector (Thorlabs Inc). The MFCA signal was measured with a phase sensitive amplifier (Model SR 830, Stanford Research). The X–Y stage table was made of MLA-K modules driven by step motors. All measurements were computer controlled.

3 Results

The spatial distributions of the amplitude of the MFCA signal are presented in Figs. 2 (side view) and 3 (top view). The wavelength of the pumping laser beam was 480 nm. In both figures, a considerable decrease in amplitude is observed in the MFCA signal from the implanted layer.

A typical profile of the amplitude of the MFCA signal measured along the black line (see Fig. 3) is presented in Fig. 4. From such profiles the signal amplitudes for implanted and non-implanted regions can be read off. The decrease in signal amplitude

Fig. 2 Amplitude distribution of the modulated free-carrier absorption (MFCA) signal for a Au^{2+} implanted silicon sample (*side view*)

Fig. 3 Amplitude distribution of the modulated free-carrier absorption (MFCA) signal for a Au^{2+} implanted silicon sample (*top view*)

in the implanted region is larger for shorter wavelengths of incident light. In general, the signal amplitude in the implanted region is considerably smaller than the amplitude of the MFCA signal in the substrate.

Fig. 4 Sample profile of the amplitude of the modulated free-carrier absorption (MFCA) signal along a length in a sample (*black line* marked in Fig. 3). The implanted region is between coordinates 1 mm and 3 mm. The wavelength of the illuminating light was 520 nm. The decrease in amplitude of the MFCA signal equaled 75 times

Fig. 5 Comparison of values for the optical absorption coefficients of non-implanted and Au^{2+} -implanted silicon samples. *Black diamonds* are experimental values of the optical absorption coefficient β of the non-implanted silicon: $\beta(1.54 \text{ eV}) = 960 \text{ cm}^{-1}$, $\beta(1.88 \text{ eV}) = 3048 \text{ cm}^{-1}$, $\beta(2.39 \text{ eV}) = 13509 \text{ cm}^{-1}$, $\beta(2.59 \text{ eV}) = 24578 \text{ cm}^{-1}$. *Full circles* are the values of the optical absorption coefficients of silicon $\times 45$. *Full squares* are the values of the optical absorption coefficients of Au^{2+} -implanted layer for the same energies of photons of the illuminating light computed using Eq. 1

From measurements of the MFCA amplitude profiles for the energies of the four laser beams (corresponding to wavelengths 480 nm, 520 nm, 660 nm, 808 nm), the optical absorption coefficients of the implanted layer were computed (Fig. 5). For different energies, the optical absorption coefficients of the implanted layer are about

Fig. 6 Spatial distribution of Au^{2+} ions in silicon computed in the SRIM program

45 times larger in value than the optical absorption coefficients of the Si substrate. The values of the optical absorption coefficients of the Au^{2+} implanted layer were computed using

$$\beta(\lambda) = \frac{-\ln(k)}{d}, \quad (1)$$

where d is the thickness of the implanted layer, k the ratio of the amplitudes of the MFCA signals in the implanted region and in the non-implanted region of the sample. Equation 1 is valid when the lifetime of the carriers in the implanted layer is much smaller than the lifetime of carriers in the substrate.

Using the SRIM computer program, the thickness of the implanted layer was found to be $d = 800 \text{ \AA}$ (Fig. 6). The SRIM program enables computations of the spatial distributions of implanted ions as a function of the distance from the surface of the sample. Computations were performed for a given type of ion, their energy, and a given implantation dose. The value of the thickness of the implanted layer, called also the implantation depth d , is necessary for computations of the optical absorption coefficient of the implanted layers.

4 Conclusions

Multi-wavelengths MFCA experiments performed on Au^{2+} -ion-implanted silicon samples indicated that the values of the optical absorption coefficients in the implanted layer increase in value by about 45 times relative to that of non-implanted silicon. A strong decrease is also seen in the lifetime of carriers in the implanted region relative to that in the non-implanted region of about $\tau = 10 \mu\text{s}$. Interpreting the observed

decrease in the MFCA signal amplitude as only a result of decreasing carrier lifetime is not possible and nor is it possible to interpret the decrease as a result of a considerable increase in the surface rate of carrier recombination. One can conclude though that measuring changes in value of the optical absorption coefficients of the implanted layers are possible with this multi-wavelength MFCA method and interpret the result within a relatively simple model. In general, the MFCA method proved effective at visualizing implanted regions in silicon samples.

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