PHOTOTHERMOACOUSTIC EFFECT IN ION-BEAM IMPLANTED Si-BASED STRUCTURES

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We present the results of investigations of the photothermoacoustic (PTA) effect in ion-beam implanted silicon-based structures. The factors, which influence the PTA-transformation and, hence, the image contrast formation in the PTA-microscopic studies of these structures, are established. The conclusion is drawn that significant changes of the PTA contrast are related to the spatial distribution of elastic stresses arising during implantation.

Ion implantation (II) is one of the principal doping methods of materials in the production of semiconductor devices of electronics. A strict perfect accomplishment of the II operations requires the development of methods of control over the implantation dose, its homogeneity, and the impurity distribution profile, which always posed rather complex problems. The traditional methods of control are destructive and need, in some cases, the manufacture of contacts to a specimen or even the development of special testing structures. Of course, this does not ensure the reliability and rapidity of the control procedure. Moreover, it is impossible to execute the control during the II process itself.

The described drawbacks can be overcome, to a certain extent, with the use of the methods based on the PTA effect that consists in the generation and transmission of heat waves excited in a solid by an electromagnetic radiation with modulated intensity. The power of PTA methods in a study of the II process is based on the fact that, in such a process, a partial disturbance of the crystal lattice by impurity ions occurs. Since the incorporation energy for impurity ions exceeds the binding energy of atoms in a semiconductor lattice by 10^2—10^3 times, this leads to an avalanche-like process accompanied by the formation of successive displacements in the crystal lattice and by the appearance of strain fields. Optical, thermal, and mechanical properties of a material change, which influences the generation and propagation of heat waves in the specimen. Moreover, these changes are proportional to the dose of implanted ions.

The importance of investigations carried on in this direction is conditioned by the following reasons:

— first, PTA methods, in particular PTA-microscopy, allow one to obtain the information on the distribution of local values of the thermal and elastic parameters of specimens;

— secondly, PTA-microscopy allows one to study the peculiarities of a spatial distribution of these parameters in inhomogeneous structures;

— thirdly, because a PTA-response is formed as a result of the successive transformation of the energy of modulated light into thermal waves and then into acoustic waves, the characteristics of the latter will be determined by the optical, thermal, and mechanical parameters of a specimen.

The use of lasers as emission sources in investigations of the PTA effect has led to the development of various instrumental realizations of the PTA-based methods such as the gas microphone, piezoelectric, and "mirage" methods, the probe beam deviation method, etc. By focusing the laser emission on a micron-size spot and raising the modulation frequency, one can appreciably localize, in principle, the controlled region, by increasing a detection limit by $\geq 10^3$ times as compared with the traditional conductivity measurement methods. This allows one to control the II process in the preset regions of a formed structure.

We note that the information obtained by PTA methods depends on the method of registration of heat waves [1]. Upon the gas microphone recording, the obtained information is mainly determined by thermal parameters of a specimen. In methods that record the displacements in a specimen (e.g., the auxiliary beam deflection method, interferometry-based and piezoelectric methods), the information is additionally determined by specimen's elastic and thermoelastic parameters. In the method of photomodulation of the optical reflection, a change of the optical reflection coefficient of a semiconductor is recorded under the irradiation of a semiconductor by a laser beam [2, the first reference]. In this case, the changes of $(\Delta R/R)$ related to changes of the nonequilibrium carrier concentration and temperature are taken into account. Just basing on these methods, the investigations of the PTA effect in various ion-implanted structures have been carried out for two last decades at scientific laboratories throughout the world. The studied structures have become a basis for industrial measuring complexes. In particular, the "Thermal-Wave" firm produces the equipment which realizes the method of photomodulation of the optical reflection for the on-line control over the II process directly during the technological cycle of manufacture of semiconductor structures (for details, see [2, the second reference]).

We have investigated the PTA effect in semiconductor materials, by using the method of a piezoelectric record of the PTA-response. A comparative analysis shows that such a method is most sensitive and attractive due to a better processing speed, the wide frequency range, and the absence of various limitations that are imposed on specimens by other recording methods. Here, a laser emission plays the role of the initiator of heat waves. Moreover, the influence of a thermal or elastic heterogeneity is manifested in the heterogeneous heating of a specimen in the volume, where the emission interacts with the medium, as well as in the form of a change of the amplitude and phase of a heat wave propagating from the irradiated zone with the subsequent transfer of these changes to an acoustic wave.

At the same time, despite the availability of the great number of papers devoted to the study of the PTA effect in semiconductors, their number concerning PTA-microscopy with the piezoelectric recording of signals is rather small. In particular, this fact is related to the absence of a universal model of the mechanism of the PTA effect in condensed media in a broad range of modulation frequencies of electromagnetic radiation, to a possible influence, e.g., of the inhomogeneous spatial distribution of elastic parameters of the medium on the PTA-transformation, etc.

The indicated facts complicate both the comprehension of a nature of physical processes that occur upon the absorption of a modulated laser emission and the establishment of their essence. As a consequence, the analysis of PTA-images meets certain difficulties. Therefore, the investigations, which would allow one to elucidate the mechanism of PTA-response formation in the II regions of semiconductor materials (the piezoelectric method of signal recording), are obviously topical and are the content of this work.

The next types of specimens were selected for the investigations:

1) p-type Si wafers (KDB-20, boron-doped, 20 $\Omega\cdot$cm, $N_a \approx 7 \cdot 10^{14}$ atom/cm^3, implanted with 100-keV P$^+$ ions with doses: 0.05, 0.2, 0.5, 1.0, 5.0, 10.0 μC/cm^2);
2) n-type Si wafers (KEF-7.5, phosphorus-doped, 7.5 $\Omega\cdot$cm, $N_a \approx 5 \cdot 10^{14}$ atom/cm^3, implanted with 100-keV P$^+$ ions with doses: 0.1, 0.12, 0.14 μC/cm^2);
3) p-type Si wafers (KDB-40, boron-doped, 40 $\Omega\cdot$cm, $N_a \approx 5 \cdot 10^{14}$ atom/cm^3, implanted with 40-keV B$^+$ ions with doses: 0.01, 0.02, 0.03, 0.04, 0.05 μC/cm^2).

Earlier, we have experimentally shown [3, 4] that the method of PTA-microscopy (piezoelectric recording of signals) allows one to visualize the topological pattern of the region of implantation. In addition, in the obtained PTA-images, we observed inhomogeneities which are related to the instability of the process of implantation for some reasons, e.g., due to fluctuations of the ion beam current, the presence of regions with a high concentration of defects on a semiconductor wafer, etc. The dependence of PTA-signals on the implantation dose is presented in [5]. This dependence can be regarded methodically as a calibration curve for the estimation of implantation doses under conditions of the stability of implantation itself and, respectively, of measurements of the PTA-signal.

A more difficult task is the visualization of the II regions under the low-dose irradiation with lighter ions implanted with a low energy. In [6, 7], p-type Si wafers doped with 40-keV boron ions were investigated. Each wafer had an interface that separated the implanted region from that without implantation. In all the cases, we succeeded to detect this interface in the PTA-topograms. This fact indicates the sensitivity level of PTA-microscopy to diagnose small implantation doses, which is of importance in the technology of the production of integrated circuits, where the threshold voltages are the most critical to the values of small doses under ion implantation.

The PTA-images (amplitude and phase) of a KDB-20 sample implanted with 100-keV P$^+$ ions are shown in Fig. 1. The graphs of the amplitude and phase changes of signals along the LS—LS^1 arrow, as shown in the images, are presented in a lower part of Fig. 1.

Analogous PTA-images for the p-Si samples (KDB-40, $N_a \approx 5 \cdot 10^{14}$ atom/cm^3, implanted with 40-keV B$^+$ ions, the dose $D = 0.05$ μC/cm^2) are shown in Fig. 2.

We pay our attention to the PTA phase and amplitude topograms (Fig. 2), in which the latent defects in a substrate are observed. Such defects as scratches, microcracks, and microvoids in the near-surface layers of a solid can lead to a considerable change of the contrast in PTA-images due to a change of the PTA-signal in

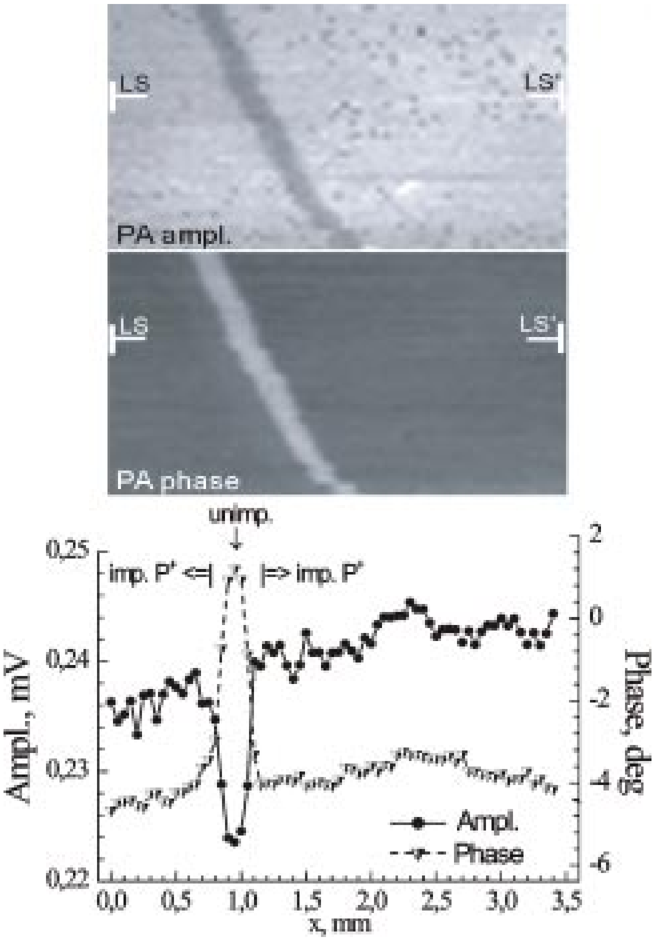

Fig. 1. PTA-images of the Si wafer region implanted with P^+ ions

regions, where they exist. It is connected with that the above-mentioned defects are the regions with broken uniformity of a material and are a considerable obstacle for the propagation of heat waves. Just for this reason, the material inhomogeneities, which differ from the surrounding material by their thermophysical and elastic properties, can be visualized in PTA-images. These defects cannot be visualized by optical investigations. In this case, we have got the PTA-images of polished technological defects that appeared in the near-surface layer at the stage of a final treatment of Si wafers, i.e., before the ion implantation.

Further, different topological contrasts of the regions, where the admixture ions have been introduced, are observed, as seen in Figs. 1 and 2. The interface between the doped and undoped regions of a specimen is distinctly visualized. We point out that no difference in the optical contrasts from the mentioned regions of a Si wafer was observed. The treatment of the Si wafer surface corresponded to the roughness level $R_z < 0.05$ μm.

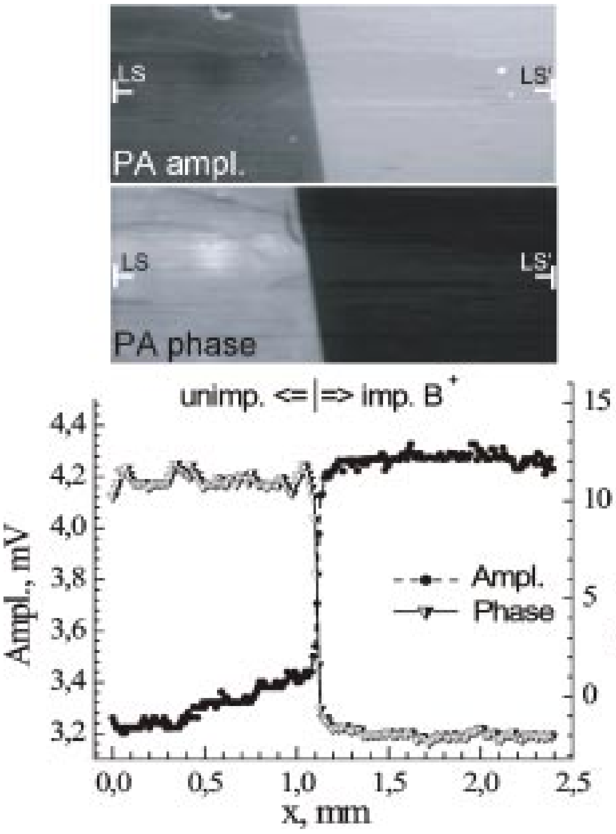

Fig. 2. PTA-images of the Si wafer region implanted with B^+ ions

In both cases (different dopants and different concentrations of implanted ions), the amplitude of a PTA-signal in the doped region of a sample was greater than that in the undoped region. At the same time, the ratio of the phases of PTA-signals in these regions was opposite.

Therefore, the rather considerable change of the PTA-signal value under the passage through the interface between the doped and undoped regions of a sample and, consequently, the change of the contrast of these regions in the obtained images are a clearly ascertained experimental fact. The probable reasons for the PTA-response change can be either a change of the thermal parameters of a material due to the II process, or a change of the mechanical properties of a specimen, e.g. the appearance of residual stresses in the ion-implanted region of a semiconductor crystal.

First, we consider the case of a possible influence of changes, which are caused by a change of the thermal conductivity in the implanted region of a Si wafer, on the PTA-response value. As known, the incorporation of atoms with masses different from that of atoms of a semiconductor material into the crystal lattice, leads to a change of the electron and phonon spectra [8]. According to the case under consideration, an ion-implanted specimen can be schematically presented as a certain two-layer structure with different thermal conductivities, k_{impl} and k_{unimpl}, respectively. We note that a change of the charge carrier concentration at these values of implantation doses has almost no influence on the electron component of thermal conductivity [9]. At the same time, it is known [10] that ion implantation leads to a change of the phonon component of k. The value of $\mathrm{k}_{\text{impl}}/\mathrm{k}_{\text{unimpl}}$ was $\sim 10^{-2}$ for Si and GaAs specimens implanted with Si^+ ions. The results of relevant experiments are presented in [10].

On the other hand, we note that a change of the thermal conductivity stipulates a change of the characteristic parameter, namely the length of thermal diffusion (l_{th}). This parameter determines the PTA-response excitation region. The estimation of l_{th} for implanted specimens gives 1—2 μm, which is less by one order of magnitude than l_{th} for unimplanted samples. Therefore, the change of the thermal conductivity coefficient, while passing through the interface between the undoped and doped regions of a semiconductor material, can significantly influence, at first sight, the value of a PTA-response. However, taking into account our experimental conditions, namely

— piezoelectric recording of the PTA-response,

— the case of a strong optical absorption at $\lambda = 0.4880\ \mu$m,

— the relation between the thermal conductivities of the implanted and unimplanted layers of a sample, $k_{\text{impl}}/k_{\text{unimpl}} \approx 10^{-2}$,

— the relation between the sample thickness (d) and the thermal diffusion length (l_{th}), $d/l_{\text{th}} \approx (3 \div 4) \cdot 10^2$, —

and the results obtained in [11] and in the well-known classical papers on PTA [12] and elasticity theory [13], we can neglect the influence of the thermal characteristics of a specimen on the PTA-response. Indeed, in the case under consideration, the conditions for the surface excitation of an acoustic wave are realized. That is, the PTA-response will be determined mainly by the elastic and thermoelastic properties of a specimen that can differ significantly, while passing from the undoped to doped region of a Si wafer.

We have found previously [14] that the mechanism of the thermoelastic effect allows investigating a stressed state of solids. Direct experiments carried on the model samples have demonstrated that the PTA-effect is sensitive to the presence of elastic stresses in a solid. Moreover, its relative change depends on the sign of constant stresses (tension–compression) relative to the direction of thermoelastic deformations.

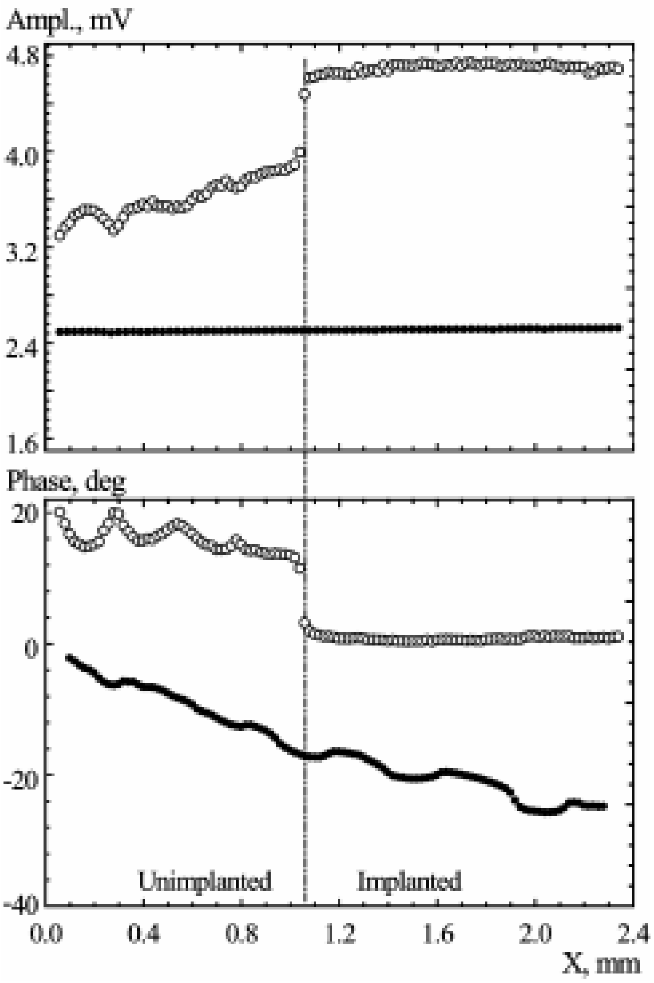

Fig. 3. Graphs of a change of the amplitude and phase shifts of a PTA-signal for a specimen with interface between the unimplanted and implanted regions before (empty symbols) and after (filled symbols) the annealing ($T = 850$ °C, 30 min)

As known [15], the implantation of B^+ and P^+ ions into the interstitial region of silicon leads to the appearance of compression stresses. In this case, for B^+ ions (the ion radius $R = 0.89$ Å), stresses are smaller than those for P^+ ions (the ion radius $R = 1.10$ Å). Moreover, it was experimentally shown that the changes of the amplitude and phase of PTA-signals, while passing from the unimplanted to implanted regions of specimens, have the same character [see Figs. 1 (P^+) and 2 (B^+)].

This fact indicates that the mechanism of changes of a PTA-signal in the ion-implanted regions is of the same nature.

In addition, we point out also that the technological process of annealing at 850 °C ($t = 30$ min) favors the recrystallization of the Si lattice and, consequently, the relaxation of internal stresses that have appeared during II. The linear scans of PTA-signals for one of the lines are presented in Fig. 3. Empty symbols are obtained before the annealing of a sample, while filled symbols present the results after the annealing. It can be seen that a change of the PTA-response on the interface between the doped and undoped regions almost disappears as a result of annealing. Therefore, we may consider that the change of a PTA-response is probably connected with residual stresses that have appeared in the near-surface layer of the crystal-Si substrate as a result of II.

In [16], we have made a theoretical analysis of the thermoelastic excitation of elastic waves due to the light energy absorption (the pulse regime of modulation) in a stressed medium with regard for the influence of nonlinear elastic and thermoelastic constants. Basing on the proposed model for the mechanism of PTA-effect formation in stressed media, a relative change of the PTA effect is calculated, and it is shown that this change in the stressed region of a medium is determined by the linear and nonlinear elastic and thermoelastic material constants. Using the analytical expressions obtained, the approximate estimation of elastic stresses σ_0 in the ion-implanted region of a Si wafer gives: $\sigma_0 = 10^8 \div 10^9$ Pa. Such values of stresses are close to those known from literature [17].

Thus, the investigations of ion-implanted Si-based structures carried on by the method of PTA-microscopy allow us to conclude that the peculiarities of the PTA-transformation and, respectively, a contrast of PTA-images of such structures are stipulated by the residual stresses that arise during the incorporation of an impurity in the near-surface layer of a semiconductor.

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ФОТОТЕРМОАКУСТИЧНИЙ ЕФЕКТ В IОНОЛЕГОВАНИХ СТРУКТУРАХ НА ОСНОВI Si

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Резюме

Наведено результати досліджень фототермоакустичного (ФТА) ефекту в іонолегованих структурах на основі Si. З'ясовано фактори, що впливають на процес ФТА-перетворення і відповідно на формування контрасту зображень в дослідженнях з ФТА-мікроскопії цих структур. Встановлено, що суттєві зміни ФТА-контрасту пов'язані з просторовим розподілом напружень, що виникли при імплантації.