Change of electrophysical properties of the Si(111) and Si(100) surface in the process of ion implantation and next annealing

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The change in the electrical properties of the Si(111) and Si(100) surfaces during ion implantation and subsequent annealing was studied. The possibilities of controlling of the electrophysical properties of the Si(111) and Si(100) surface layers by the implantation of ions of alkaline and alkaline-earth elements are analyzed. Some electrophysical properties of semiconductors containing p- and n-structures and the possibilities of their application in electronics are discussed.

Keywords: silicon, implantation, semiconductor, nanosize, surface, silicide, single crystal, ion, dose.

Introduction

Silicon, traditionally being the base material of modern microelectronics, is in the center of attention of researchers around the world. Nanocrystal silicon as a substrate for integrated circuits remains to date the main material of microelectronics [1-3]. This allows the creation of hybrid thin-film structures. In addition, silicon is a cheap material, the production of which is established in industry in huge volumes [4].

The traditional approach to controlling the properties of semiconductor materials is based on the use of alloying processes with their impurities. The task is to choose the right alloyed with the necessary properties, optimize the level and method to obtain crystalline perfect highly homogeneous nanocrystals or epitaxial films that do not contain defects and impurities that could significantly affect the properties of the alloyed material. Applied to many important problems, this problem was successfully solved, which ensured the rapid progress of semiconductor electronics [5].

With some degree of conventionality, nanomaterials can be divided into two classes:

1) artificial low-dimensional structures, such as two-dimensional quantum valleys, one-dimensional quantum filaments and zero-dimensional quantum dots; an increase in thermoelectric figure of merit in such systems is associated with an increase in the dependence of the density of electronic states on energy with a decrease in dimension [6].

2) Nanocrystalline materials (NCs) and nanocomposites, in which the suppression of lattice thermal conductivity due to phonon scattering by inhomogeneities with a scale from units to tens of nanometers is considered as the main mechanism for increasing efficiency [7, 8].

As a result of the above, silicon micro- and nanoelectronics technologies based on silicon and AIIIBV and AIIBVI semiconductors are specifically different from each other. Traditionally, silicon instrument structures are built in the bulk of silicon in the form of alloyed regions, and on the surface in the form of thin-film layers. Hence the search for various solutions to overcome the disadvantages of silicon. For example, strained silicon layers are used in which it becomes a direct-gap semiconductor, or strained heterostructures [3] (including multilayer ones) are grown on it from materials with close lattice parameters, for example, germanium [9] or silicides [10]. Another approach is to search for specific "niches" for silicon in which it would manifest itself as a more "profitable" material. Here are examples of such "niches":

- integral spintronics [11, 12], where silicon has no competitors in the length of the coherence of the spin [13];

- integrated optoelectronics [14-16], where silicon can be used as an integrated optical waveguide;

- Integrated nanoplasmonics [17], where conductive metal buses surrounded by silicon are good plasmon nanowave guides.

In these areas, various hybrid thin-film heterostructures from metal, dielectric and semiconductor films on silicon are obtained.

This article discusses the physical mechanisms for changing the electrical conductivity of an n-type Si(111) surface during the implantation of alkaline ions of various doses.

Investigation of the properties of silicon layers doped by ion implantation

The relevance of these studies is due to the desire to maintain at a new stage in the development of microelectronics - in the transition to nanoelectronics and optoelectronics - silicon and silicon technology as the base ones. Ion implantation turned out to be one of the most effective ways to create silicon nanostructures [18].

We studied the effect of implantation of Ba$^+$ ions and alkaline elements with E_0 =1 keV with a different dose and subsequent heating on the electrophysical properties of the surface layers of Si(111) and Si(100).
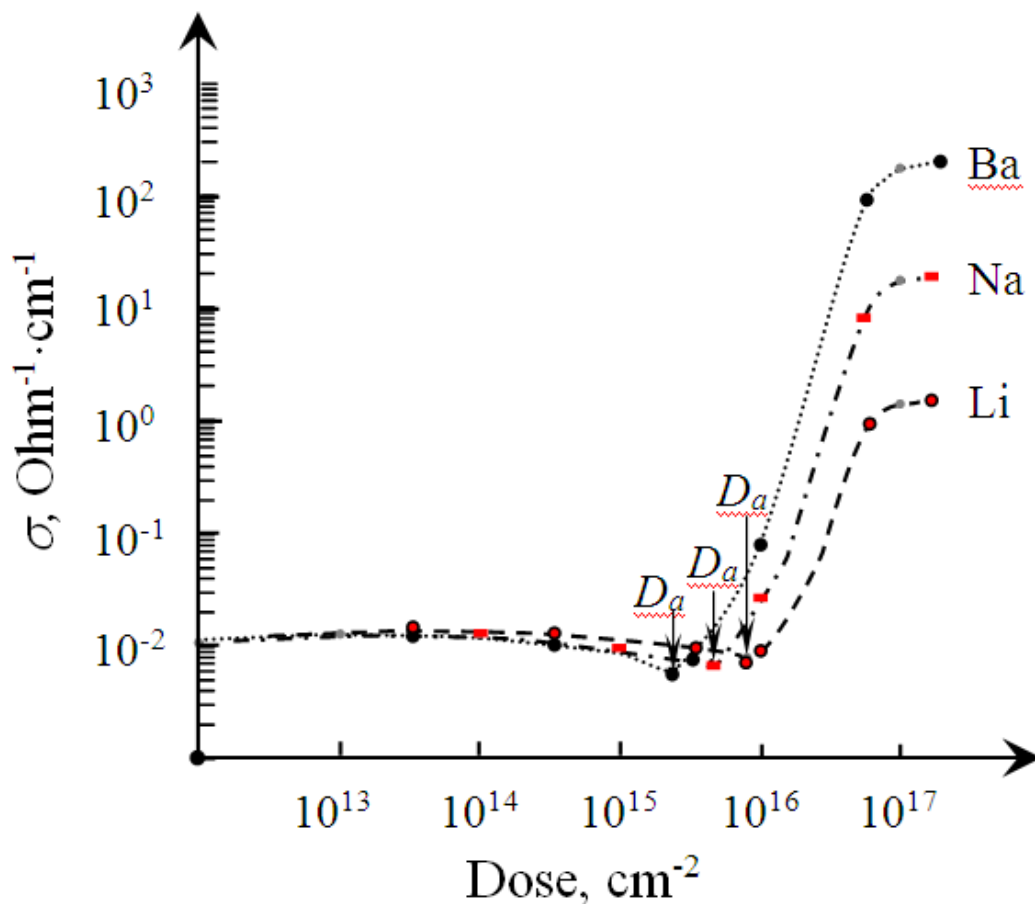

Figure 1. Dependences of the electrical conductivity σ of the Si(111) surface on the implantation dose of ions (Li$^+$, Na$^+$, and Ba$^+$) with an energy of E_0 =1 keV.

Studies of changes in the electrical conductivity of an n-type Si(111) surface during implantation of Ba$^+$, Na$^+$, and Li$^+$ ions with an energy of E_0 =1 keV with a different dose revealed that ion implantation (regardless of the type of ion to a dose of $D = 8 \cdot 10^{14}$ cm^{-2} practically does not lead to a change in σ (Figure 1) [19-22]. This is probably due to deep penetration due to channeling of implantable ions and their small contribution to surface conductivity. It should be noted that implantation of Ba$^+$ ions and alkaline elements with a dose of $D \approx 10^{14}$ cm^{-2} leads to an increase in the electron concentration at the donor levels and to the beginning of the splitting of donor levels, which should result in an increase in σ

[23-26]. However, at these doses, the Si(111) surface region is strongly disordered, which leads to a decrease in the surface conductivity; the latter compensates for the contribution of an increase in the donor concentration to the increase in σ. The validity of such a mechanism is indicated by the minima in the dose dependences of σ (Figure 1). With an increase in the dose of implanted ions, a sharp increase in σ is observed up to $D = 10^{17}$ cm^{-2}.

Figure 2 shows the dependences of the electrical conductivity σ of the Si(111) surface implanted with Li$^+$, Na$^+$, and Ba$^+$ ions with an energy of $E_0 = 1$ keV with a dose of $D = 2 \cdot 10^{17}$ cm^{-2} on the temperature of the subsequent annealing. It can be seen that, starting from the temperature T_{cr} corresponding to the recrystallization of the implanted region, a sharp increase in σ is observed. In our opinion, the formation of nanosized films of LiSi, NaSi, and BaSi is observed at T = T_{cr}.
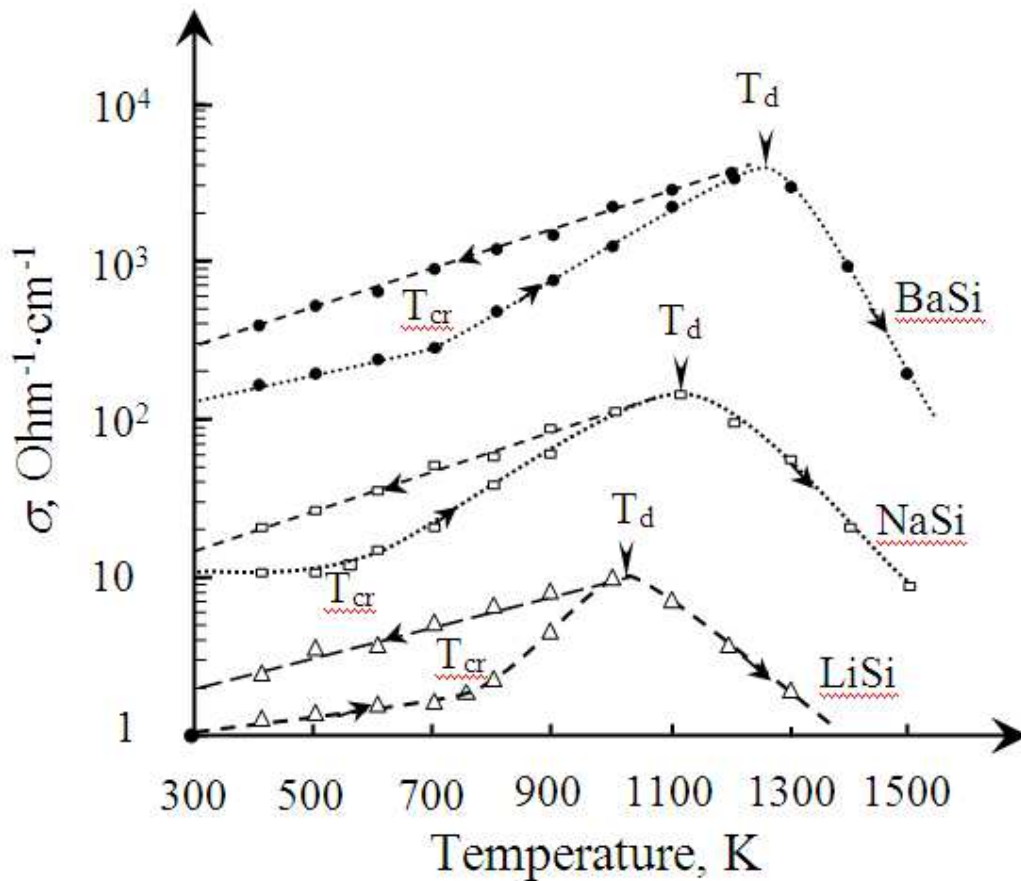

Figure 2. Dependences of the electrical conductivity σ of the Si(111) surface implanted by ions (L$^+$, Na$^+$ and Ba$^+$) on the annealing temperature.

At a temperature T>T_d, the destruction temperature of the silicide film σ decreases. Assessment of the thickness of the silicide film by the method of layer-by-layer Auger analysis showed that, at an ion energy of $E_0 = 1$ keV, the film thickness is 5-6 nm (or 50-60 Å). When the silicide films are cooled from T_d to 300 K, the electrical conductivity of the silicide films decreases linearly, which is characteristic of degenerate semiconductors.

Conslusion

The results of recent experimental studies of the transport properties of semi-conductor silicides of barium, sodium and lithium have shown the possibility of their use in modern electronics. A feature of these materials is their good technological compatibility with silicon, due to which they are promising for thermoelectric silicon-based heterostructures. Significant progress in improving the thermoelectric properties of barium, sodium, and lithium silicides has been achieved by alloying.

It was established that implantation of Ba^+, Na^+ and Li^+ ions with an energy of E_0 =1 keV (regardless of the type of ions) up to a dose of $D = 8 \cdot 10^{14}\,cm^{-2}$ practically does not lead to a change in the electrical conductivity of the n-type Si(111) surface. With a further increase in the dose of implanted ions, a sharp increase in σ is observed up to $D = 10^{17}\,cm^{-2}$, then saturation occurs.

Studies of the temperature dependence of the electrical conductivity σ (T) of ion-implanted samples revealed sharp bending at the crystallization temperature T_{cr} corresponding to the formation of nanosized films - BaSi, LiSi, and NaSi silicides. It is shown that the presented silicide films exhibit an almost linear temperature dependence of electrical conductivity like semiconductors up to the decomposition temperature of silicides T_d = 1050-1250 K [27].

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