Formation of Monocrystalline Silicon Nanowires Using Low-Energy Ion Irradiation

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Abstract—In this work we have proposed a technique which can be used to fabricate monocrystalline silicon nanowires on a silicon wafer surface by forming specially designed extended structures with a negative slope angle of side walls and their subsequent oxidation by irradiation with low-energy oxygen ions at a temperature of 400°C. The shape and sizes of the structures were chosen first so that the process of oxidation would not modify the central part of the nanowire and keep the monocrystallinity and doping level of the initial silicon and, second, to provide the electrical insulation of the nanowire from the wafer. The dependence of the oxidation depth on the temperature and duration of plasma irradiation as well as the electrical properties of the resulting oxide are studied.

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INTRODUCTION

The development of monocrystalline silicon nanowires is a topical problem in connection with the rich potential abilities for their applications in nanodevices [1], e.g., highly sensitive biological detectors and sensors. Special attention is paid to the development of techniques which can be used by fabricating monocrystalline nanowires directly on the surface of standard silicon wafers compatible with the process of fabricating microelectronic devices. The authors of this work are efficiently developing radiation techniques to change the atomic composition of materials in thin layers under the action of irradiation with charged particles. Recently [2] we proposed a method to fabricate silicon nanowires by irradiating the structures formed on the surface of a monocrystalline wafer with a combined ion beam. In this case the insulation of the nanowire from the substrate is achieved at the expense of overlapping zones of damage, which arise as a result of the scattering of the ion-beam proton component, while the oxidation accompanies the zone of defect generation in silicon. To achieve such a method of nanowire formation, it is necessary to use composite ion beams with energies of ~1–2 keV.

In contrast to the abovementioned approach to insulating the nanowire from the substrate, in this work we propose a technique of plasma action by oxygen ions of low energies on monocrystalline silicon. In this case, no particles of high energies are required; this lowers the radiation load on the elements of the devices. To insulate the nanowire from the substrate, we propose the use of linear silicon structures with a negative slope of side walls as the initial structures; as a result, the width of these structures is minimal in the regions adjacent to the silicon wafer. The oxidation regimes are chosen so that the zone at which the structure contacts the wafer is completely transformed into oxide, which electrically insulates the nanowire from the substrate. The basic idea of the proposed technique to form nanowires consists of ensuring this shape and size of the initial structure, which protects the central part of the nanowire from modification and keeps the monocrystallinity and the properties of the bulk monocrystal after the process of oxidation are carried out.

One important feature of the proposed technique for fabricating silicon nanowires is the formation of oxide by irradiation with low-energy oxygen ions. In comparison with the traditional techniques of thermal oxidation in water vapor or dry oxygen, the application of irradiation makes it possible to substantially lower the temperature of the oxidation process. For example, the basic oxidation regime used in this work to obtain an oxide of ~50 nm thick proceeds at a temperature of 400°C, while temperatures of 800°C and higher are required to obtain a similar oxide by the standard thermal process [3]. A reduction in the temperature of the oxidation process substantially decreases the thermal load on the device to be formed, and this is an important advantage of the proposed oxidation technique when compared with traditional ones.

In this work, to create linear structures in silicon with a negative slope angle of side walls, we used a setup with a focused ion beam (FIB), which allowed us to etch a complicated shape. However, since methods of the plasma chemical formation of a negative profile by silicon etching have been being developed in recent years [4], the proposed technique can be used to form
nanowires within the framework of standard microelectronics technologies.

EXPERIMENTAL

Silicon oxide was formed on the surface of silicon wafers of the n and p types doped with phosphorus and boron with a resistance of 0.006 Ohm cm and 0.03 Ohm cm (concentration $10^{19}$ cm$^{-3}$ and $4 \times 10^{18}$ cm$^{-3}$, respectively) with an orientation of [001]. The treatment in oxygen plasma was carried out on a Copra Cube (CCR-Technology) setup equipped with an RF plasma source with an excitation frequency of 13.56 MHz. The sample was heated with the help of a ceramic heater on a massive polished metal plate whose temperature was controlled by a thermocouple. In this case, the metal plate with the sample was insulated from the earth; i.e., it was at a floating potential caused by a higher mobility of the electron plasma component compared with that of the ionic one.

To measure the flux density and energy spectrum of ions bombarding the sample surface, we used a specialized detector in the form of a Faraday cup (CCR Technology) equipped with an input diaphragm at which a back potential of $-50$ V was applied to exclude the effect of an electron component on the measurements of the ion current parameters. The energy spectrum of ions was built by measuring the dependence of the ion current value on the value of a positive back voltage applied at the Faraday cup.

The samples were treated in oxygen plasma at a pressure of oxygen in the chamber of $p = 2.3 \times 10^{-3}$ Torr and a power of the RF discharge of 1000 W.

The initial and irradiated samples were studied using X-ray photoelectron spectroscopy (XPS). The spectra were obtained on a Qantera (PHI) scanning spectrometer, allowing us to carry out a layer-by-layer analysis by the precision etching of the sample surface with argon ions and the successive registering photoelectron spectra. The resolution of the spectrometer measured by the width of the Au4f7/2 line at its half-width amounted to 1.2 eV.

The spectrum of Si$_2$-$\delta$-electrons was decomposed into single lines corresponding to various chemical states of silicon atoms with the use of three lines corresponding to silicon atoms being in the form of oxides SiO$_2$ (Si$^{4+}$) and SiO (Si$^{2+}$) and in the form of a nonoxidized silicon (Si$^0$).

The examination of sample microstructure was carried out on a Titan (FEI) transmission electron microscope (TEM) (accelerating voltage is 300 kV) with the use of a GIF2002 (Gatan) spectrometer of electron energy losses. The samples for TEM investigations were prepared on a setup with a Helios Nanolab 600 (FEI) focused ion beam.

The formation of the initial bar in Si with a negative profile was carried out on a setup with a Helios Nanolab 600 (FEI) focused ion beam at an energy of gallium ions of 30 kV and ion current of 93 pA. We used plates of monocrystalline silicon of a [100] orientation coated with a Ta protective metal layer of 50 nm thickness as the initial billets.

To study the electrophysical properties of silicon oxide fabricated by plasma oxygen irradiation, we used the method of creating an MOS structure (metal–oxide–semiconductor). The layer of oxide to be studied was formed by oxygen irradiation on a plate of doped monocrystalline silicon. A metal gate with area $S$ of about 0.5 mm$^2$ was formed on this layer using the thermal deposition of a thin layer of gold (100 nm). The MOS structure was studied using the techniques of volt–amperometry and volt–faradometry on a setup designed to study the properties of Keithley 4200–SCS semiconductors and an Agilent 4980A LCR measurer in the frequency range $10^{-3}$ Hz–2 MHz and voltages $\pm 10$ V, which were the basis for the conclusions of the properties of the working layer of the insulator.

RESULTS AND DISCUSSION

The possibility for reducing the temperature of the oxidation process of monocrystalline silicon when using treatment in an oxygen plasma is caused, first and foremost, by the energy component of the ion beam bombarding the surface of the silicon sample. Figure 1 shows an experimental energy spectrum of the beam of oxygen ions used in the formation process of silicon oxide. Two peaks, 12.5 and 30 eV, are