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CLEANING OF THE SURFACE OF SILICON STRUCTURES IN THE TECHNOLOGY OF VERY LARGE-SCALE INTEGRATED CIRCUITS WITH THE USE OF RAPID HEAT TREATMENT

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Results of investigation of the quality of cleaning of the surfaces of silicon, silicon dioxide, and aluminum films with the use of rapid heat treatment prior to the application of a photoresist and the influence of such cleaning on the deviation of the linear dimensions of a topological pattern subjected to etching are presented. All the results are considered in comparison to the traditional methods of surface cleaning. The parameters of the elements of very large-scale integrated circuits manufactured with the use of rapid heat treatment for cleaning of the surfaces of various thin-film materials coated on silicon are presented.

Microminiaturization of semiconductor devices and very large-scale integrated circuits (VLSICs) has imposed new requirements upon the cleaning of the surfaces of materials used in the process of their manufacture. The cleaning involves the removal of organic photoresist films or vacuum oil films deposited on the surface of the substrate, ash residues of the plasma-chemical etching, and ionic contaminants appearing as a result of the vaporization of moisture and the sublimation of oil traces and residues of organic and inorganic nature. In this connection, it is of interest to investigate the possibility of using rapid heat treatment (RHT) of silicon plates with various films (SiO_2, Si_3N_4, Al) applied to their surface for this purpose [1].

For such investigations we exposed the back side of the silicon plates to the radiation of xenon lamps with a pulse duration of 50 msec for an energy density from 60 to 120 J/cm^2 and to the radiation of halogen lamps with a pulse duration from 1.4 to 8 sec for a power density of 35 W/cm^2. This made it possible to heat the silicon plates from 400 to 1200^{o}C. The surface treated was coated with a layer of photoresist and subjected to photolithography. By the deviation of the dimension of an element from its topological value we judged the adhesion of the photoresist to the surface and consequently the quality of its cleaning. For comparison, we cleaned the surfaces of a part of the plates by chemical treatment and correlated the dimensions of the elements obtained in this case with the dimensions of the elements obtained on the plates cleaned by the RHT method. In addition, a comparative analysis of the quality of cleaning of the surface of silicon and aluminum was performed by the method of Auger spectroscopy.

The results obtained (Figs. 1 and 2) point to the following facts. An increase in the temperature of treatment of the surfaces of aluminum films by the RHT method for the purpose of their cleaning decreases the deviation of the dimensions of the elements of a photolithographic pattern subjected to etching. In the case of treatment of the surfaces by pulses of second duration providing their heating to a temperature of 475^{o}C, the deviation of the dimensions is analogous to that in the case of chemical cleaning. An increase in the temperature to 525^{o}C makes it possible to decrease the deviation of the topological dimensions by a factor of 1.3. This is explained by the fact that in the case of rapid heat treatment, an increase in the temperature of the surface treated makes it possible to remove moisture from the intergranular boundaries more completely than in the case of chemical treatment; as a consequence, the adhesion of the photoresist to the surface of an aluminum film is higher in the first case. As the temperature of the aluminum film increases, the contaminants that can appear on its surface as a result of the deposition, especially oil traces, are also removed more completely. Further increase in the temperature to 550^{o}C does not change the deviation of the dimensions of the elements formed, which points to the fact that the cleaning is completed at a temperature of lower

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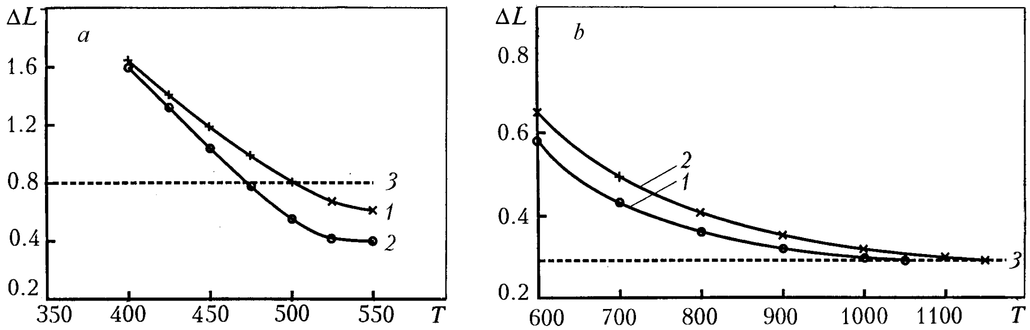

Fig. 1. Dependence of the deviation of the line width of Al 0.8 μm thick (a) and SiO_2 0.29 μm thick (b) in chemical etching on the temperature of cleaning of their surfaces by the method of RHT with pulses of second (1) and millisecond (2) duration prior to the application of a photoresist; 3) deviation of the line width in the case of chemical cleaning of the surfaces of Al and SiO_2 films. ΔL, μm; T, ^{o}C.

than 550^{o}C. Treatment of the surface by pulses of millisecond duration does not qualitatively change the pattern, except that results analogous to those obtained in the case of treatment by pulses of second duration require higher temperatures, which is explained by the much shorter effective time of treatment in the first case. Cleaning by pulses of second duration is more advantageous because the time of treatment is markedly longer in this case [2] and consequently the quality of the cleaning is higher.

An analogous situation is observed in the case of cleaning of silicon dioxide films by the RHT method: an increase in the temperature of treatment decreases the deviation of the dimensions of the elements subjected to chemical etching. In the case of treatment by pulses of second duration at T = 1050^{o}C, the deviation is similar to the deviation in the case of chemical cleaning. Further increase in the temperature does not decrease the deviation and it remains equal to that in the case of chemical cleaning, which points to the fact that the cleaning is completed at T = 1050^{o}C. However, unlike aluminum films, cleaning of silicon dioxide by rapid heat treatment requires higher temperatures. This is explained by the fact that the OH group is removed from the surface layer of a silicon dioxide film in this case. Since the binding energy of the OH group with silicon is high, a fairly high energy and consequently a high temperature are necessary to break it. The same qualitative pattern is observed in the case where pulses of millisecond duration are used for cleaning, except that results analogous to those of treatment by pulses of second duration require heating to higher temperatures. This is explained, as in the case of aluminum films, by the fact that the effective time of treatment is longer when pulses of second duration are used for cleaning in comparison to the cleaning by millisecond pulses.

The above results are confirmed by the data obtained from a comparative analysis of the Auger spectra of the surfaces of silicon and aluminum cleaned by rapid heat treatment and chemical treatment (Fig. 2). As is seen, rapid heat treatment by pulses of second duration gives a marked positive effect, which is demonstrated by the marked increase in the peak of Si^0 (pure silicon) and the decrease in the peak of C in comparison to the initial state of silicon after ion-implantation doping and Al after deposition. This means that such treatment decreases the content of both the organic contaminants (decrease in the peak of C) and the number of bound states and increases the number of free states on the surface (appearance of the peak of Si^0 and an increase in it). The results obtained in the case of chemical treatment are similar to the results obtained in the case of rapid heat treatment by millisecond pulses. However, the results obtained in the case of rapid heat treatment by pulses of second duration exceed them. The reasons are completely the same as in the case of evaluation of the adhesion of the photoresist to the surface of films cleaned by different methods.

To elucidate the possibility of using rapid heat treatment in the technology of manufacture of VLSICs for the purpose of cleaning the surfaces of various materials, we evaluated the influence of the quality of cleaning on such parameters as the threshold voltage, the drain current of *n*- and *p*-channel transistors, and breaks and short-circuits in different levels of metal as well as on the reliability of the devices based on these VLSICs.

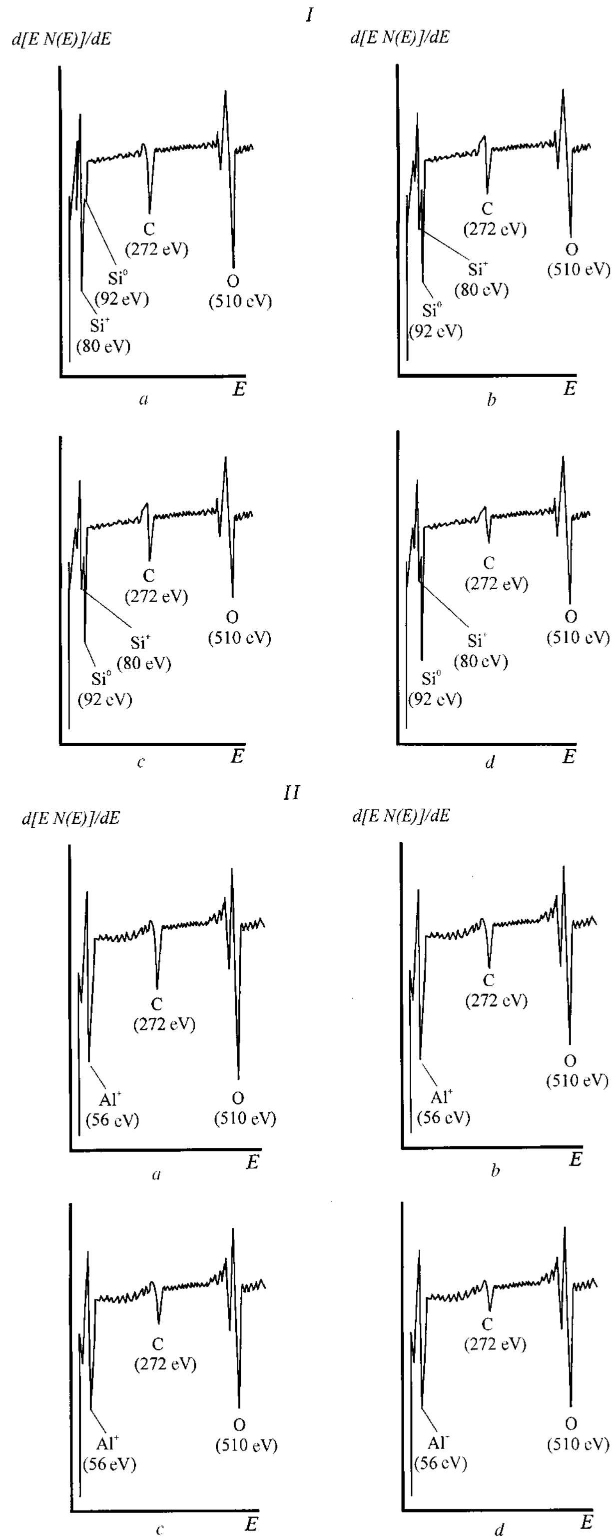

Fig. 2. Auger spectra of the silicon surfaces (I) (after ion-implantation doping (a), cleaning of the surface by the standard method (b), rapid heat treatment by pulses of millisecond duration (c), RHT by pulses of second duration (d)) and the aluminum surfaces (II) (after deposition (a), cleaning of the surface by the method of chemical treatment (b), the RHT by pulses of millisecond duration (c), RHT by pulses of second duration (d)). Along the axes, rel. units.

For investigations we used plates, part of which was subjected to surface cleaning by the standard technology, i.e., to chemical treatment in liquid solutions, and the other part of which was cleaned using rapid heat treatment by pulses of second duration. The regime of treatment, namely, the pulse duration and the power density, were provided by heating of silicon plates in the temperature range 500–1050^{o}C depending on the material of the surface treated.

A comparative analysis of the parameters of the storage circuits, obtained by means of statistical processing of the data of measurements of more than 100 VLSICs for each type of cleaning of the surface, made it possible to establish the following regularities. The mean value of the threshold voltage is 0.75 V for an *n*-channel transistor on the plates cleaned by the standard methods and 0.81 V for an *n*-channel transistor on the plates cleaned by the RHT method, which is 0.06 V higher. For a *p*-channel transistor, the threshold voltages are close and equal to 1.00 V in the case of standard cleaning and to 1.02 V in the case of cleaning by the RHT method. An increase in the threshold voltage of the *n*-channel transistor in the structures cleaned by the RHT method is explained by the increase in the concentration of electrically active boron due to its additional activation in the *p*-pocket and in the region of additional doping of the channel because of the heating of the silicon substrate to 1050^{o}C in the process of cleaning of the surface. For the *p*-channel transistor that is formed in the *n*-pocket, an increase in the electric activity of phosphorus leads to an increase in the electron conduction of the pocket, which compensates for the increase in the hole conduction in the region of the channel which is due to the electric activation of boron.

The mean value of the drain current of the *n*- and *p*-channel transistors on the plates the surface of which was cleaned by the RHT method is lower than that of transistors on the plates cleaned by the standard methods (8.19 and 7.62 mA for the *n*-channel transistor and 3.16 and 2.91 mA for the *p*-channel transistor respectively). Such behavior of the drain current is also explained by the additional activation of the impurity and its insignificant redistribution in the drain-source regions and in the region of additional doping in comparison to the plates cleaned by the standard method.

The use of rapid heat treatment for surface cleaning makes it possible to substantially decrease the percentage of defects caused by the break of the first and second levels of plating. The breaks of the first and second levels of plating are lower by a factor of 4.67 and 1.83, respectively, than those on the control samples. This is explained by the fact that on the plates cleaned by the RHT method and subjected to etching the width of the plating is larger than that on the control plates. The larger width of the plating in the first case, as has been shown above, is due to the increased adhesion of the photoresist to aluminum cleaned by the RHT method prior to the application of the photoresist. In this case, side deviations of the dimensions of an aluminum film subjected to etching are smaller, especially at the steps of the surface relief where the film is thinner than on the horizontal surface and consequently where side deviations caused by the etching are maximum. As a result, the number of defects significantly decreases due to the break of the first and second levels of plating on the surface relief. This result is especially important for manufacturing VLSICs with submicron dimensions since the side deviation as a result of the etching of different layers should be minimum in this case.

Thus, rapid heat treatment of the back side of initial silicon plates and plates with a film of silicon dioxide or aluminum makes it possible to adequately clean the surface and to increase the adhesion of a photoresist to it due to the removal of moisture from the intergranular boundaries or the OH group from the surface layer of the film and due to the sublimation of organic contaminants, the decrease in the bound states, and the increase in the free states on the surface. In this case, rapid heat treatment by pulses of second duration is more advantageous because of the increased effective time of treatment.

The use of rapid heat treatment for cleaning of the surface of materials used for manufacturing VLSICs does not deteriorate their electric parameters and reliability operation under various conditions and increases the good-to-bad VLSIC ratio due to the decrease in the variation of the parameters of the active structures.

NOTATION

T, temperature, ^{o}C; ΔL, deviation of the line width of the photolithographic pattern, μm; E, energy of electrons, eV; $d[EN(E)]/dE$, relative units.

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