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CONTROL OF THE PROPERTIES OF THIN-FILM SYSTEMS WITH THE USE OF PULSED PHOTON TREATMENT

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We have developed a radically new technological process of making very large-scale integrated circuits, which has no analogs and is based on the use of fast heat treatments for forming gettering layers, silicon oxidation, annealing of ion-doped layers, fusion of phosphoro- and borophosphorosilicate glasses, forming silicides, and increasing the thermostability of aluminum metallization.

The majority of electronics companies working with topological norms of 0.3 μm or less have practically completely changed over from traditional methods of heat treatment to fast methods using various heat sources. This called for the investigation and development of processes minimizing the action of prolonged high-temperature treatments on thin-film structures (films of semiconductors, dielectrics, metals, and silicides) on silicon and the realization of control of their properties by changing regimes of fast thermal treatment (FTT). In the Scientific-Production Association "Integral," such investigations were launched in the 1980s. Let us consider the results obtained in the course of the investigation of the influence of FTT on the crystal structure of the silicon surface, the processes of gettering, silicon oxidation, annealing of ion-doped layers, fusion of low-melting-point glasses, increasing the thermostability of aluminum films, and silicide formation.

Photon treatment of a silicon surface having disturbances caused by chemicomechanical polishing (Fig. 1a) with coherent radiation in the adiabatic regime (pulse duration of 30 nsec) providing surface-layer melting removes them and permits obtaining a practically atomically flat surface (Fig. 1b). Such a treatment of the surface of a plate subjected to mechanical polishing by diamond suspensions with a grain size of 1–3 μm leads to the disappearance of mechanical disturbances and deep scratches (Fig. 1c). This is confirmed by the appearance in the diffraction pattern of vertical rods that are due to the two-dimensional diffraction from the surface atomic layers [1]. Their elimination is associated with the appearance in the region of disturbances of capillary pressure forces and two crystallization fronts: perpendicular and parallel to the surface being treated, as a result of which there appears a surface with a perfect crystal lattice.

Treatment of the nonworking surface of silicon plates with coherent radiation under heat-flow conditions (pulse duration of ~1 μsec) providing its melting leads to the appearance in the irradiation zone of tensile stresses, which also remain after the irradiation is terminated. This is due to the large temperature gradient acting for a long time at the liquid-crystal silicon interface (Fig. 2a). The subsequent prolonged thermal treatment of such structures at 1100°C in a dry oxygen medium causes stress relaxation with the formation of dislocations and oxygen precipitates that are the gettering centers of fast-diffusing impurities and point defects (Fig. 2b). The efficiency of gettering by these centers is confirmed by the behavior of the precipitates of copper preliminarily introduced into silicon, which are practically completely getterized by these centers (dark dots in Fig. 2c). The application of the above gettering method permits obtaining epitaxial films with a defect density two orders of magnitude lower than without the thus-formed gettering layer [2].

Photon treatment of the planar surface of a silicon plate in the oxygen medium with incoherent radiation under thermal-balance conditions (pulse duration of more than 0.05 sec) providing heating to 1100°C permits forming on it a thin layer of silicon dioxide. In so doing, the oxidation process in the initial stage deviates from the generally accepted Deal–Grove model, which is due to the formation of negative oxygen ions resulting from the tunneling and

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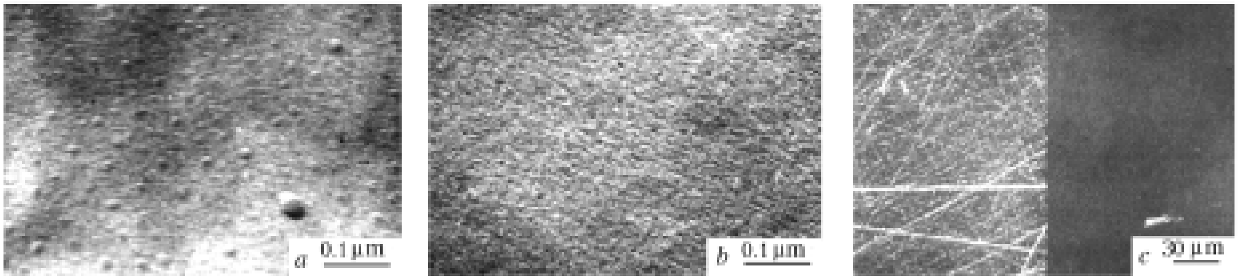

Fig. 1. Silicon surface microrelief upon chemicomechanical polishing (a), chemicomechanical polishing followed by laser treatment (b), and chemical treatment (on the left) and subsequent laser treatment (on the right) (c).

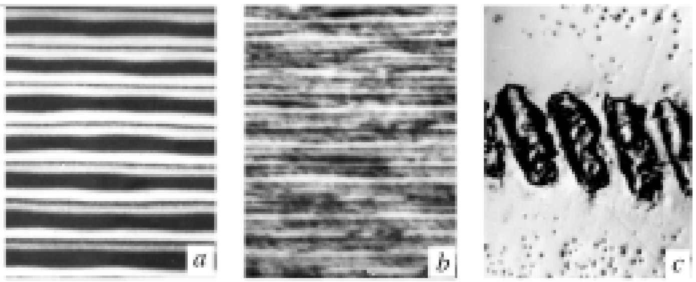

Fig. 2. X-ray topograms of the silicon plate after laser treatment (a) and after subsequent prolonged thermal treatment (b), as well as view of the decorated surface of silicon with copper precipitates (dark points) in the region of laser action (c).

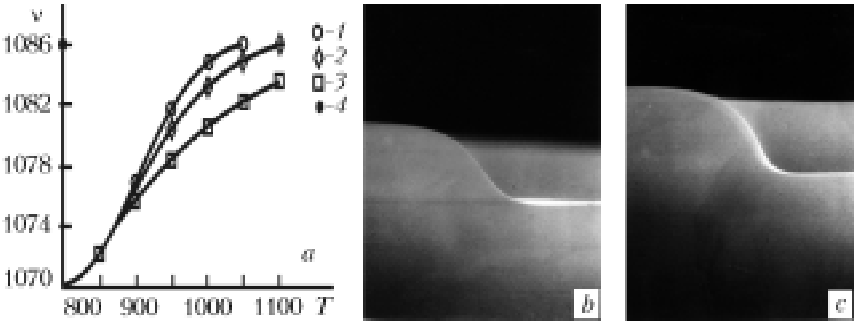

Fig. 3. Change in the structure of the low-temperature SiO_2 film after fast treatment at various heating rates (1–3) and prolonged treatment 4 (a) and view of a step of phosphorosilicate glass upon fusion by the method of fast (b) and prolonged (c) thermal treatment: 1) 75; 2) 100; 3) 325°C/sec; 4) T = 1100°C, t = 20 min. ν, cm^{-1}, T, °C.

thermionic emission of electrons from the surface layers of a semiconductor material. Because of their small sizes, they feature a high diffusivity in an oxide and have a lower activation energy of the oxidation process. Photon treatment of the silicon surface under the above conditions permits obtaining on it an oxide of thickness of up to 20 nm [1].

Photon treatment under thermal-balance conditions providing heating to 1000°C of layers of silicon dioxide and fusible glasses obtained by deposition at low temperatures causes a change in the structure of dielectric films (Fig. 3a). The basic processes thereby are the formation of silicon–oxygen bonds, strengthening of the force of these bonds, and reduction of their stresses, the absence of microcrystal inclusions, and additional oxidation of silicon at the silicon–silicon dioxide interface. The continuation of these processes in the course of treatment leads to a densification of dielectric films, a doubling of breakdown voltages, a two- to tenfold decrease in the leakage currents, and a decrease

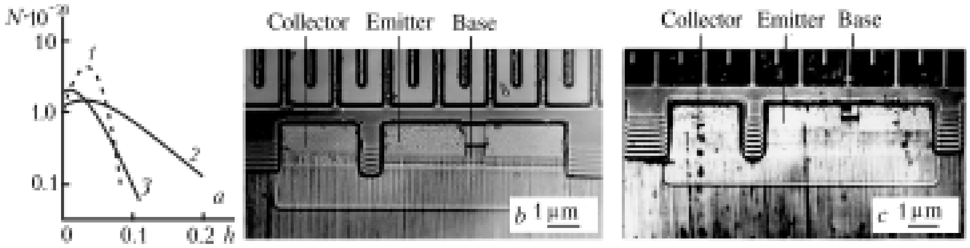

Fig. 4. Phosphor distribution profiles (a) and cross section of the *n-p-n* transistor obtained with the application of fast (b) and prolonged (c) thermal treatment: 1) calculated by the Linhard–Scharff–Schiott theory; 2) $T = 900^{o}$C, $t =$ 30 min; 3) on fast thermal treatment. E = 30 keV; D = 300 μC/cm^2. N, cm^{-3}; L, μm.

Fig. 5. Morphology of the silicon-doped film upon deposition (a) and prolonged (b) and fast (c) treatment.

by two orders of magnitude in the charge density at the semiconductor–dielectric boundary. In the case of fusible glasses, their fusion is observed. It promotes a considerable smoothing of the surface relief and is more effective under fast thermal treatment (Fig. 3b) than in the case of prolonged treatment (Fig. 3c) [3].

In investigating the photon treatment of ion-doped silicon layers under thermal balance conditions providing heating to 1100^{o}C, we established the fact of restoration of the crystal lattice of silicon disturbed as a result of the ion doping. This process occurs due to its solid-phase recrystallization. In so doing, the maximum activation coefficient of the introduced admixture and the absence of the formation of compensating centers and deep levels are provided. In this case, the admixture redistribution is much smaller than in the case of prolonged treatment (Fig. 4a) but considerably larger than predicted by the diffusion theory. This phenomenon is due to the diffusivity doubling at the expense of the appearance of an electric field at cooperative diffusion of the mobile carriers and admixture [2]. An important point of such treatment is the fact that the decay of radiation defects occurs bypassing the stage of the appearance of their complex aggregates. This is confirmed by the absence of the effect of boron rejection by phosphor (Fig. 4b), which at prolonged treatment (Fig. 4c) is due to the additional formation of vacancies at the expense of dissociation of the phosphor–vacancy complexes.

Important results have been obtained in investigating the aluminum–silicon system subjected to pulsed photon treatment. The action on this system (Fig. 5a) of incoherent radiation under thermal-balance conditions providing heating to 53 0^{o}C, as opposed to prolonged thermal treatment, leads to a balancing of the surface tension forces in the film. This permits forming an equilibrium structure in the aluminum film without the formation of bumps on its surface (Fig. 5b). Such a structure proves to be stable to subsequent prolonged treatments at temperatures, at which they are performed, lower than the FTT temperature, and for pure aluminum films, it decreases by an order of magnitude the depth of its penetration into the silicon. In the case of silicon-doped aluminum films, it causes no silicon redistribution over the film thickness and reduces by an order of magnitude its rejection at the interfaces and along the aluminum grain boundaries, thus decreasing the values of the metal–semiconductor contact resistance and the resistance of the metal film on the whole [4].

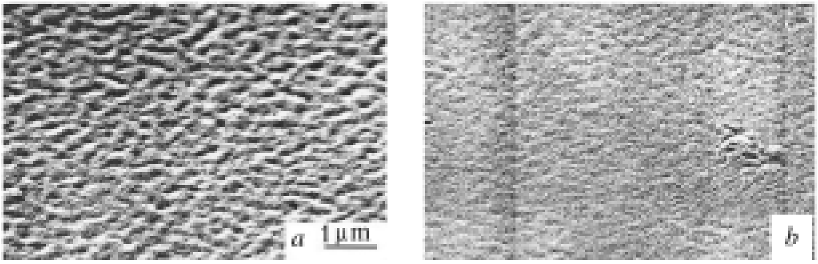

Fig. 6. Morphology of the $TiSi_2$ film formed with the application of prolonged (a) and fast (b) thermal treatment.

Photon treatment with incoherent radiation under thermal-balance conditions of the titanium–silicon system with the aim of forming titanium disilicide permits its synthesis at a temperature of 100°C lower and in a time several times shorter than at prolonged thermal treatment. This provides the possibility of forming layers of titanium disilicide in one stage without its interaction with the lower-lying silicon dioxide, as opposed to prolonged thermal treatment where titanium disilicide is formed in two stages in order to exclude this interaction. In so doing, the titanium disilicide surface relief is less developed (Fig. 6a) than in the case of prolonged thermal treatment (Fig. 6b) and decreases as its temperature increases. An important result of the titanium disilicide formation with the use of pulsed thermal treatment is the obtaining at a certain temperature of a titanium silicide simultaneously containing all of its known phases, which is impossible to achieve by prolonged thermal treatment. In the course of these investigations, for the first time the possibility of nitriding the surface layer of refractory metals by their fast thermal treatment in a nitrogen medium was shown [5].

The results obtained permit the conclusion that the radiation heating of any heat-insulated material for a time shorter than or equal to the establishment in its bulk of thermal balance is followed by a decrease in the activation energy caused by a change in its structure, phase composition, and electrophysical parameters.

On the basis of the investigations performed, technological processes have been developed, the use of which permits forming active elements on epitaxial films of thickness 0.6 μm, which is the physical limit for bipolar very large-scale integrated (VLSI) circuits with electric parameters and an operation speed exceeding the analogous parameters obtained by the traditional technology. It should be noted that the degree of integration of VLSI circuits obtained by the proposed technology is two times higher and the operation speed advantage is a factor of 2.25. An important fact is that such an increase in the degree of integration and operation speed is attained without lowering the technological standards of design, i.e., without decreasing the size of the photolithographic pattern.

NOTATION

T, temperature, ^{o}C; t, time, min, sec, nsec; ν, frequency, cm^{-1}; E, doping energy, keV; D, doping dose, $\mu C/cm^2$; P^+, phosphor ion; N, bulk concentration, cm^{-3}; h, thickness, μm.

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