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OPTICAL PROCESSES IN SILICON AND MICROELECTRONIC STRUCTURES BASED THEREON UPON INTERACTION WITH HIGH-ENERGY RADIATION

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Results of technical studies are presented on formation of light fluxes in silicon and integral structures based thevlon. Effects of these light fluxes upon electric parameters of planar triode structures of integral circuits are considered. It has been shown that under irradiation by high-energy particles consumed and leakage currents of integral circuit are increased. Ways to decrease these effects are proposed.

1. INTRODUCTION

Emission in visible and infrared spectral region has been recorded in our experiments when silicon was bombarded by alpha particles, protons, helium, hydrogen and nitrogen ions. This emission is observed when the primarily kicked-off atom is decelerated.

The light flux starts propagating, and further course of this process depends upon optical properties of the crystal studied. Propagating in semiconductors and integral structures, the emerging radiation causes generation of current carriers and photocurrent. Carrier formation intensity depends upon optical transparence of the semiconductor and energy levels of the dopants.

2. METHOD OF SIMULATION AND RESEARCH

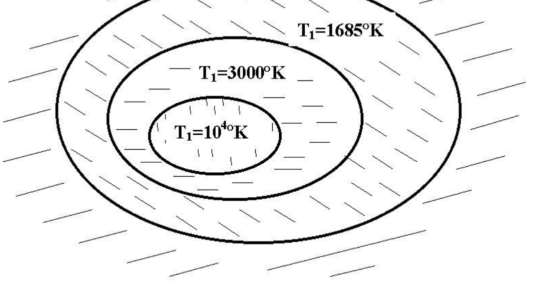
2.1. LIGHT FLUXES IN INTEGRAL STRUCTURES UNDER HIGH-ENERGY IRRADIATION

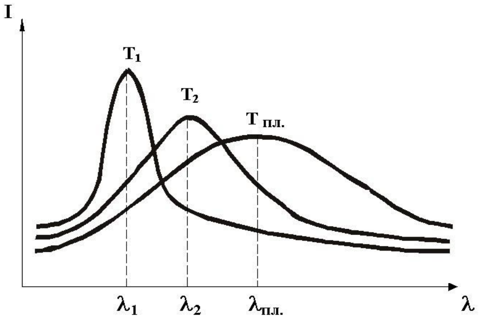
We report here our experimental results on the effects of light flash formation and the accompanying light fluxes in visible and IR ranges. This occurs when corpuscular fluxes affect solid-state elements of electronic equipment and parameters of integral circuits.

In the defect cascade formation theory, pair interactions of atoms are assumed. However, with irradiation by high-energy particles, the liberated energy affects large groups of atoms. The transfer of energy leads to heating of a limited region of the substance to high temperatures.

According to calculations [1] based on simple microscopic laws of thermal conductivity, energy is liberated in the form of heat and is propagated by the laws of thermal conductivity (“temperature wedge”). The temperature rises and falls very quickly ($\tau_{heat} = 5\cdot10^{-12}$ s, $\tau_{cool} = 2\cdot10^{-11}$s) in a small volume (diameter ~60 A) containing 103 atoms. The substance inside the “wedge” is in overheated state with a melted zone in the center. Formation of the “temperature wedge” is accompanied by expansion of the substance in it, which leads to formation of mechanical stresses around it, and to generation of dislocation loops.

According to [2], a region containing about 104 atoms is heated up to melting (Fig.1), being intensively mixed. Subsequent rapid cooling causes distortions of the crystal lattice to be preserved as dislocation loops and micro-regions with new orientation. Such regions are called “displacement wedges”. Direct experimental observation of thermal peaks is rather difficult, and their studies were carried out by observing physical processes that could be explained by heating (in particular, phase transitions in alloys of complex composition). Difficulties in interpretation of the data obtained are due to the fact that results of these studies could be also explained by defect migration or accumulation processes.





Серия: Физика радиационных повреждений и радиационное материаловедение (83), с. 154-157.

Fig.1. Thermal peak T_1, being cooled due to its short-wave emission, leads to heating and melting of the adjacent region (T_2, T_{melt}), which, in turn, transforms the energy in a region of longer wavelengths, where it goes out of the silicon sample because of its transparence

Sputtering experiments can explain, to some extent, the dynamic processes that proceed when ions are introduced into a crystal, as the influence of ions results in large concentrations of low-energy ions in the spectrum of emitted particles [2]. However, explanation of this maximum in terms of particle evaporation from the surface is also rather ambiguous.

An important consequence of the formation of "wedges" of any type is that their appearance, existence and disappearance should lead to emerging radiation in the light spectral region. Therefore, a question has arisen to study light emission processes under introduction of high-energy particles.

2.2. GENERATION OF IR-RADIATION

Experimental studies have shown the existence of radiation in the nearest IR spectral region [1]. Microphotometry of photographic plates that recorded IR radiation coming from silicon affected by alpha-particles (with an intermediate IR light filter or without one) have shown that approximately 1/3 of the radiation is in the region above 1.1 μm, and nearly 2/3 – in the 0.76… 1.1 μm region.

2.3. EFFECTS OF GENERATED AND PROPAGATING ELECTROMAGNETIC RADIATION ON RADIATION STABILITY OF INTEGRAL CIRCUITS UNDER IRRADIATION

To explain the processes in the solid state under introduction of high-energy particles and to calculate the degree of illumination caused by thermal flashes, let us consider the case of silicon being bombarded by fast neutrons.

Assuming the energy of bombarding neutrons to be E_n = 2 MeV and the conversion coefficient N = 0.5 [3], we put that about 1 MeV will be converted into electromagnetic radiation.

Putting the intensity of fast neutrons under irradiation in a nuclear reactor as $n_1 = 5\cdot 10^9$ neutrons$\cdot$cm$^{-2}\cdot$s^{-1}, we can obtain the energy released during deceleration of neutrons in the semiconductor

$$\begin{aligned} E_T &= E_n N n_1 = \frac{2MeV}{n}\cdot 0{,}5\cdot 5\cdot 10^9 n\cdot cm^{-2}\cdot s^{-1} = \\ &= 5\cdot 10^{15} eV\cdot cm^{-2}\cdot s^{-1} \approx 8\cdot 10^{-4} J\cdot cm^{-2}\cdot s^{-1}. \end{aligned} \qquad (1)$$

This value is practically equivalent to the illumination of one lux.

When an atomic devise is exploded, the flux of fast particles can reach the densities of 10^{12} - $5\cdot 10^{13}$ neutrons$\cdot$cm$^{-2}\cdot$s^{-1} [4]. This means that internal regions of integral circuits and semiconductor instruments (in particular, *p-n* transitions) that come under such conditions will be subject to illumination of 10^2 – 10^5 lux.

When the primarily displaced particles interact with silicon, effects are observed that can be explained in terms of Seitz's "thermal peaks" and Brinkman's "displacement wedges" formation theories.

If we consider that IR radiation is caused only by energy spent for defect formation during introduction of the particles, then it would be not exact to say that one half of all the energy, on the average, is spent for the defect formation, and the second half is lost in collisions not accompanied by displacement of atoms. In fact, nearly two-thirds of the energy of introduced alpha-particles or primarily displaced particles is emitted in the IR region. In addition, it should be accounted for that interaction of particles with a solid-state body not accompanied by displacement of atoms from the lattice sites would also contribute to the energy of IR radiation.

Theoretical calculations have shown that parameters of silicon semiconductor instruments (diodes, triodes, planar structures of integral circuits) can get changed under bombardment by fast particles not only due to defects and recombination centers [5] formed by the influence of accelerated particles, but also due to IR and optical illumination of p-n transition.

Silicon band gap at 300 K is 1.09 eV. When the wavelength of the light flux generated in the integral structure is changed from 380 nm to 1.33 μm, the energy of light quanta is dectrased from 3.5 eV to 1.2 eV, and at 13 μm wavelength, the propagating radiation quanta have energies of 0.1 eV.

Silicon is transparent for IR light above 1 μm and has high reflectance in the all the light range. Silicon oxide is transparent in visible and IR spectral ranges.

At light quantum energies above 1.09 eV, all over the silicon volume generation of charge carriers will be observed, which will recombinate in the region of electron-hole transitions, giving rise to photocurrent under the flux of bombarding high-energy particles. This process is due to the transition of silicon electrons from the valence zone to the conductivity zone (Fig.2).

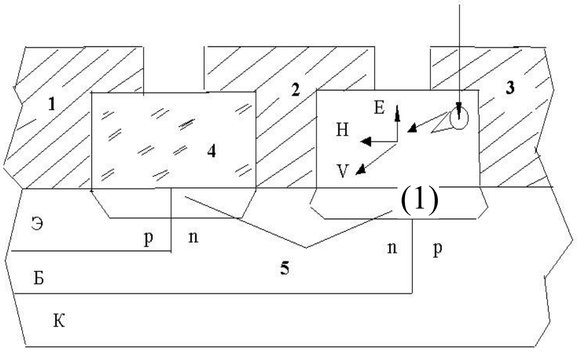


Fig.2. The emitter (E), base (B) and collector (C) metal outlets (1,2,3) from the corresponding regions of planar transistor structure of the integral circuit. Transparent structure of the insulating layer (4) and carrier generation regions (7) on the boundaries of p-n transitions under light fluxes (5)

In parallel with this, carrier generation is observed due to ionization of admixture atoms in the lattice sites. Activation energy of the carriers located on donor and acceptor levels is lower than the band gap width, so the carrier concentration will be increased due to transitions from the donor levels to the conductivity zone and the valence zone.

In silicon oxide, waves of both IR and visible range can propagate. They will substantially affect the carrier generation at the boundaries, as well as in surface-adjacent regions and *p-n* transitions coming to the surface or adjacent to it.

In bipolar integral circuits, the emitter transition is also within the transparence limits for the visible range waves. Its efficiency will be decreased, as the emerging photocurrent by-passes the electron-hole transition.

2.4. ATTENUATION OF ELECTROMAGNETIC WAVES IN OPTICALLY TRANSPARENT LAYERS OF INTEGRAL CIRCUITS

The question of losses in thin transparent layers of metal planar structures cannot be answered with full strictness.

The reason is that it is impossible to state exactly the boundary conditions at finite wall conductivity. Approximate methods are to be used, using a number of simplifying assumptions, as a result of which the energy flux W along the structure is proportional to the factor $e^{-l\beta z}$. The energy loss in the walls is determined as

$$-\frac{dW}{dZ} = 2\beta W = Q$$

hence the absorption coefficient is

$$\beta = \frac{Q}{2W}.$$

It can be postulated that while σ is sufficiently small, attenuation will also be small ($\beta << \alpha$).

Neglecting it, according to the presentation of the phase-time factor for electromagnetic field components

$$e^{-j(wt-\gamma z)} = e^{-\beta z)} \cdot e^{-j(wt-\alpha z)},$$

where $\gamma = \alpha + j\beta$.

Here α determines the wave phase, and β - the absorption,

We assume that, within the limits of the structure, for any of the field components

$$\frac{d}{dz} = -\beta + j\alpha \approx j\alpha .$$

This means that fields $\overline{E}$ and $\overline{B}$, as well as the energy flux W, are practically unchanged. Joule's heat losses Q are calculated using the skin-effect theory separately for each of the walls. We assume that the losses are not interacting and can thus be determined independently of each other.

The current power coming through the structure cross-section with the wave along axis Z is determined by the Z-th component of the Umov-Pointing:

$$P_z = \int [EH]_z = \int (E_x H_y - E_y H_x) ds.$$

As B and H are complex values depending on time, introducing their conjugated values, we can find for the average power of the wave propagating in the structure

$$W = \frac{1}{2}\int_0^a\int_0^b R_e\left(E_x H_y^* - E_y H_x^*\right) dxdy.$$

Omitting the derivation, which is similar to the light transducer not filled with dielectric, we can write down the absorption coefficient for an H_{01} type wave

$$\beta = \frac{1{,}29 \cdot 8{,}686\sqrt{\rho}}{\text{в}^{3/2}} \cdot \frac{py^{3/2} + \frac{1}{\sqrt{y}}}{\left(1+p^2\right)^{3/4}\sqrt{y^2-1}} \qquad (2)$$

and for the H_{11} type wave

$$\beta = \frac{1{,}29 \cdot 8{,}686\sqrt{\rho}}{\text{в}^{3/2}} \cdot \frac{p(1+p)y^{3/2} + \frac{1+p^3}{y}}{\left(1+p^2\right)^{3/4}\sqrt{y^2-1}}. \qquad (3)$$

In formulas (2) and (3) the following notation was introduced:

$$p = \frac{\text{в}}{a}; \qquad y = \frac{f}{f_0},$$

where

$$f_0 = \frac{c}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$

is the critical, or limiting, frequency.

If a dielectric with dielectric constant E is introduced into the waveguide, formulas for the absorption coefficient become more complex.

For wave E_{11}

$$\beta = \frac{1{,}29 \cdot 8{,}686\sqrt{\rho}}{\text{в}^{3/2}} \cdot \frac{1+p^3}{\left(1+p^2\right)^{3/4}} \cdot \frac{Ey^{3/2}}{\sqrt{Ey^2-1}}.$$

For wave of H_{01} type

$$\beta = \frac{1{,}29 \cdot 8{,}686\sqrt{\rho}}{\text{в}^{3/2}} \cdot \frac{Epy^{3/2} + \frac{1}{y}}{\sqrt{Ey^2-1}}.$$

For wave of H_{11} type

$$\beta = \frac{1{,}29 \cdot 8{,}686\sqrt{\rho}}{\text{в}^{3/2}} \cdot \frac{Ep(1+p)y^{3/2} + \frac{1+p^3}{\sqrt{y}}}{(1+\beta^2)^{3/4}\sqrt{Ey^2-1}}.$$

If we take Al-Si-Al structure, where n_{SiO_2} =1,45 , p= 10^{-1}, y=3, E=2,1 (для λ=0,3мкм), ρ_{Al} = $2{,}69\cdot10^{-8}$ Ohm·m, b = $3\cdot10^{-5}$ cm, a = $3\cdot10^{-4}$ cm, for the attenuation coefficient β - $0{,}733\cdot10^{4}$ dB/m = 7,3 dB/m it should be noted that propagation of the electromagnetic wave is affected by optical properties of silicon, which is transparent for the visible light at layer thickness up to 3 μm.

3. CONCLUSIONS

Experimental studies of generation and propagation of electromagnetic radiation in silicon under bombardment by alpha-particles have shown that two-thirds of the radiation propagates in the spectral region 0.9...1.1 μm, and one-third of the energy is emitted in the nearest IR range.

Therefore, to improve stability of solid-state electronic instruments with respect to penetrating radiation capable of inducing light generation, one should use dopants creating deep energy levels in the band gap.

Another possibility of improving radiation stability is the use of semiconductors that are poorly transparent or not transparent at all in the visible and near-IR range (e.g., germanium). One should also use materials that are not transparent in the visible and near-IR range as insulating layers.

As such approach can lead to certain deterioration of the characteristics of electronic instruments, a compromise is advisable, allowing substantial improvement of stability of integral circuits under irradiation.

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ОПТИЧНІ ПРОЦЕСИ В КРЕМНІЇ ТА МІКРОЕЛЕКТРОННИХ СТРУКТУРАХ НА ЙОГО ОСНОВІ ПРИ ВЗАЄМОДІЇ З ВИСОКОЕНЕРГЕТИЧНИМИ ЧАСТКАМИ

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Приведено результати технічних досліджень формування світлових потоків в кремнії і інтегральних структурах на його основі. Розглянуто вилив цих світлових потоків на електричні параметри тріодних структур інтегральних схем. Показано, що під час опромінювання високоенергетичними частками збільшуються токи споживання і токи витопу інтегральних схем. Застосування запропонованих засобів дозволяє зменшити вилив цих ефектів.

ОПТИЧЕСКИЕ ПРОЦЕССЫ В КРЕМНИИ И МИКРОЭЛЕКТРОННЫХ СТРУКТУРАХ НА ЕГО ОСНОВЕ ПРИ ВЗАИМОДЕЙСТВИИ С ВЫСОКОЭНЕРГЕТИЧНЫМИ ЧАСТИЦАМИ

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Приведены результаты технических исследований формирования световых потоков в кремнии и интегральных структурах на его основе. Рассмотрено влияние этих световых потоков на электрические параметры планарных триодных структур интегральных схем. Показано, что при облучении высокоэнергетическими частицами увеличиваются токи потреблений и токи утечки интегральных схем. Применение предложенных способов позволяет уменьшить влияние этих эффектов.