Thermal Conductivity Influence on Failures of Semiconductor ICs under Powerful EMP Action

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Abstract. Thermal transfer in semiconductor integrated circuits under external HEMP action is considered. It is shown, only some thermal conductivity components influence on value of thermal gradients, which cause failures. The account of thermal conductivity dependence of substrate IC on temperature has shown reduction of temperature magnitude of crystal heating. The hypothesis are also confirmed breakdown occurrence is possible already at lower initiated temperatures, than semiconductor melt temperature.

Keywords HEMP, semiconductor, circuit, temperature, thermal conductivity

Introduction

The action of powerful electromagnetic pulse (EMP) on semiconductor integrated circuits (IC) may be accompanied by allocation of some of heat on elements of a microcircuit. Value of an arising thermal gradient appears in direct dependence on thermal properties of the crystal material [1], first of all from thermal conductivity of the semiconductor. Value definition of thermal conductivity coefficient is enough difficult by presence of its many components, and also strong influence on temperature. However, for reception of authentic model of IC failures at EMP influence is impossible without taking into account dependence semiconductor thermophysical parameters from temperature.

Modelling

The value of die thermoconductivity is considered as constant often in models of semiconductor IC on external high-power EMP reaction used in practice. Its magnitude often corresponds to thermal conductivity at 273 K or at semiconductor melting temperature. In both cases it is an essential assumption. As under EMI action the temperature of a crystal changes gradually, for definition of critical points of arising thermal fields it is necessary to know the thermoconductivity value at various temperatures.

The theory specifies existence of several types of IC semiconductor crystal thermal conductivity [2]. Generally for the semiconductor wafer it can be written as

$$K = K\text{ph} + K\text{e} + K\text{bp} + K\text{f} + K\text{ex} + K\text{i} + K\text{s} + \ldots, \quad (1)$$

where *K*ph - the phonon component;
*K*e - the electronic component;
*K*bp - the bipolar component;
*K*f - the photon component;
*K*ex – the exiton component;
*K*i – the ion component;
*K*s – the spin component.

Despite on a rather great many components of thermal conductivity, it is necessary to note, that only one or two types of thermal conduction dominates in the concrete semiconductor at certain conditions, as a rule, and other components have minor influence. Prevalent of this or that component of thermal transfer is defined by semiconductor type, temperature, circuit manufacturing techniques and characteristics falling EMP basically.

The basic components of thermal conductivity rendering the greatest influence on thermal gradients at EMP presence were revealed in course of modelling. It is the phonon, photon, electron and bipolar transfer.

The phonon thermotransfer

The heat transfer by oscillation of semiconductor crystal lattice atoms is determining after EMP action in overwhelming majority of cases. Since the operation crystal temperature much more differs from absolute zero temperature, in the semiconductor thermal transfer by phonons takes place necessarily. Oscillations of lattice atoms are chaotic basically, and this randomness is kept even at presence of an external temperature gradient to a certain extent. In this connection to describe the movement of phonons is difficult enough, as it carries probable character. Therefore the phonon thermoconductivity caused by throw-over processes was taken into account.

As a whole, at temperature higher 293 K two factors have essential influence on heat transfer in IC:

- growth of oscillation number of phonons, carrying heat;
- growth of the interphonon's dispersion.

After thermal conductivity maximum so-called throw-over processes begin to play the basic role. Long-wave phonons do not cause thus final thermal resistance though their influence and in normal processes and in throw-over processes is often essence. With the account only these processes and with use of Keyes's formula the expressions for the phonon thermal conductivity are received in dependence on temperature at EMP presence. The hypothesis was used, that melt of IC material came then when the amplitude of thermal fluctuations of atoms reached identical to all solid bodies of interatoms distance shares:

$$\mathrm{K}_{\mathrm{ph}} = BT_m^{3/2}\rho^{2/3}A^{7/6}\frac{\theta_D}{T}, \quad (2)$$

where T_m – semiconductor melt temperature.

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A - average nuclear weight.

B - some empirical factor dependent on resistance and the module of compressibility of a material; for semiconductors *In* п 0,06;

P - material density;

T - current temperature;

Θ- Deby's temperature.

The received expressions have quite sufficient accuracy. However, at temperatures is Deby's higher essential difference between the experimental and theoretical data are observed. In general, for temperatures that are higher Deby's ones the theory of thermal conductivity of semiconductors is advanced much worse, than for a temperature range, which is lower than Deby's temperature. It is connected to sharp growth of influence inharmonious thermal oscillations. of atoms. In turn also to have to take into account static defects of semiconductor crystal as used expressions were received for ideal crystals. However, taking into account, that the lattice parameter of basic semiconductors with temperature growth changes a little bit, modified Keys's expression covers a temperature range in which failures are possible after EMP interaction. The basic calculation error is brought with presence of defects in the semiconductor.

Electronic thermotransfer

Heat transfer by charge carriers also brings the essential contribution to distribution of heating after EMP influence. The account of this type of thermal conductivity becomes important at temperatures that are higher Deby's temperature. For example, for silicon the electronic thermoconductivity grows sharply at temperatures T > 1,6 Td (i.e. is higher 1074 K). In real devices at EMP influence such temperatures arise seldom even at irreversible breakdowns. At lower temperatures the contribution of electronic thermal conductivity does not exceed 5-10 %. Nevertheless, the account of heat conductivity on carriers is obviously important for IC with high doping degree when the contribution electronic transfer is shown at temperatures of device operation. In the work the estimation of electronic thermoconductivity by functions that take into account dependence of carrier mobility on temperature and dispersion on acoustic fluctuations of lattice atoms was made. It is determined from the received expressions, that the electron conductance in many respects determines electronic thermotransfer at EMP, therefore its dependence on temperature also was defined.

The exact account of electronic thermal conductivity not always has basic value, but important to estimate its contribution quickly. If necessary, it is possible to carry out its more exact analysis for the concrete semiconductor circuit on known expression of Wideman's – France's – Lourentz's. For a fast estimation of electronic heat conductivity the formula of a kind was used:

$$K_e = \frac{(\frac{5}{2} - s)k^2\sigma T}{e^2}, \qquad (3)$$

where s - a constant received experimentally from dependence of mobility from temperature; at dispersion of electrons on fluctuations of a lattice atoms; s was accepted equal 2;

σ - electronic conductivity;

k - Boltzsmann's constant;

e - electron charge.

The received equations are fair by consideration hole as electron for semiconductors with acceptor-type conductivity. However it is necessary to specify, that they are applicable only at an assumption of elasticity of electron collisions with lattice atoms, defects, ions of an impurity, etc. This condition is fair at high temperatures. The Lourentz's number is much more difficult to define for degenerate semiconductors, semiconductors with complex structure of valent zone and also at presence of optical fluctuations. The last are observed basically at low temperatures, when effects by EMP influence practically are not shown.

Bipolar thermotransfer

The bipolar mechanism role of thermal conductivity grows with temperature rise in the IC die. After EMP influence the electron – hole pairs given birth on the hot end diffuse in a heating field, then in area with lower temperature recombine, allocating thus energy, which is approximately equal to width of bandgap. Allocated at each recombination act an energy passes in one of lattice thermal oscillation. Thus, by bipolar transport some heat is transferred. Its maximal value when the width of bandgap is much more than multiply product of Boltzmann's constant on temperature value is received.

To define bipolar thermoconductivity it is possible by next formula:

$$K_{bp} = 2L\frac{\sigma_n\sigma_p}{\sigma_n+\sigma_p}(\frac{\Delta E}{2kT}+2+r)^2, \qquad (4)$$

where σ_n – electron conductivity

σ_p - hole conductivity.

r - the factor caused by a dispersion kind of electrons in semiconductor volume after HEMP influence.

Bipolar component of thermal conductivities is additional in relation to phonon and electronic component. It is maximal at ΔE»kT.

It is determined, that thermoconductivity bipolar component is appreciable after EMP action in IC bases using germanium at temperatures above 300 K and it is well described by received expression. It also plays the big role in such semiconductors, as Bi2Te3, PbTe, PbSe. In silicon and arsenide of gallium its contribution is insignificant.

Photon thermotransfer

One of kinds of heat transfer is internally thermal radiation to which energy is transferred by a special class of carriers - electromagnetic waves. These heat carriers represented in radiation quantums essentially differ from other transport sources of thermal energy. Electromagnetic radiation transfers some energy from hot places to cold if thermal gradient is available. Therefore at EMP presence there is else one additional component of thermal conductivity, that is photon one.

As against bipolar heat transfer the photon thermal conductivity may be shown at temperatures below area of own conductivity. Results of modelling show, that in case of EMP influence in area of Deby's temperatures photon thermoconductivity contribution may become prevailing, therefore its account is extremely important. Moreover, photon heat transfer as against other mechanisms of thermal conductivity does not dissipate on lattice defects [3].

For the greatest accuracy of photon thermoconductivity definition in semiconductors with the account of dispersion of photons in volume used experimentally received formula:

$$K_f = \frac{31185\varepsilon^{3/2}}{512\pi^2}\left(\frac{kT}{\hbar}\right)\frac{m_*^2\mu_0(T_k)}{cne^3}\left(\frac{T_\kappa}{T}\right)^{3/2}, \qquad (5)$$

where ħ - Plank constant;

ε - dielectric permeability;

n - refraction factor;

m_* - electron effective weight,

It is visible, that photon thermoconductivity strongly depends on temperature ($K_f \sim T^3$), and already at $T > 300\,^0C$ it begins to bring the essential contribution to the general heat conductivity.

In table 1 there is calculated ratio K_{ph}/K_f while experimental data show still a smaller difference between phonon and photon types of thermal conductivity.

T, K	*n*-Si	*n*-Ge	*n*-GaAs
300	$4\cdot10^{-3}$	$5\cdot10^{-3}$	$6{,}5\cdot10^{-3}$
400	$0{,}9\cdot10^{-2}$	$1{,}2\cdot10^{-2}$	$2{,}2\cdot10^{-2}$
500	$2{,}9\cdot10^{-2}$	$4\cdot10^{-2}$	$6\cdot10^{-2}$
600	$0{,}9\cdot10^{-1}$	$1{,}1\cdot10^{-1}$	$1{,}5\cdot10^{-1}$
800	$2\cdot10^{-1}$	$2{,}5\cdot10^{-1}$	$4\cdot10^{-1}$
1000	$4{,}6\cdot10^{-1}$	$7{,}5\cdot10^{-1}$	$9{,}4\cdot10^{-1}$
1200	0,9	1,2	1,8
1400	2,3	2,6	3,0

Table 1. Calculated ratio between phonon and photon types of thermal conductivity for three own semiconductors

The calculations have shown that the contribution photon thermal conductivity becomes equal phonon one for many types of IC substrates after EMP actions (fig.1).

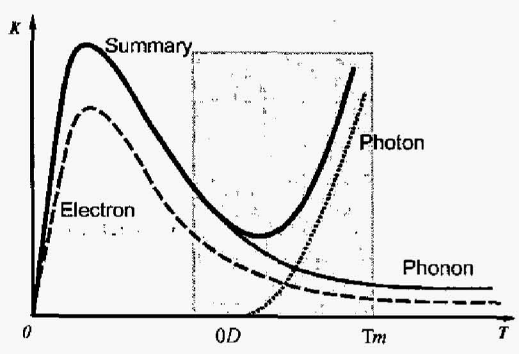

Figure 1. Influence of semiconductor thermal conductivity components on the general thermoconductivity in dependence on temperature. The shaded field is area of the most probable values of temperature after HEMP actions.

Other components of heat transfer after EMP actions bring the small contribution in general thermal conductance basically. The ion mechanism is displayed of heat transfer probable at semiconductors with significant doze ion conductivity the most. The heat transfer in this case is carried out in direction of temperature gradient by oscillations of set of charge carriers and positive or negative ions. However the role of this thermoconductivity mechanism even in semiconductors with ion conductivity is rather small. The total contribution of ion heat transfer, also exiton thermal conductivities and one's on spin waves in such semiconductors as Si, Ge and GaAs in general thermal transfer after EMP influence seldom exceeds 1%. Therefore their account did not represent interest in the calculations.

Modelling Results

Using the received formulas for the calculations of an arising temperature gradient, the analysis of probable failures in semiconductor IC was executed due to external EMP influence of high power by duration from milliseconds up to nanoseconds.

The account of thermal conductivity dependence of substrate IC on temperature has shown reduction of temperature calculation magnitude of crystal heating. Data variability at position, what K = const and K = f(T) makes more than 20 degrees (fig.2). And, speed of temperature increase at EMP nanosecond duration is higher than at microsecond duration. Thus, the hypothesis are also confirm that breakdown occurrence at EMP action is possible already at lower initiated temperatures, than melt temperature of a semiconductor material.

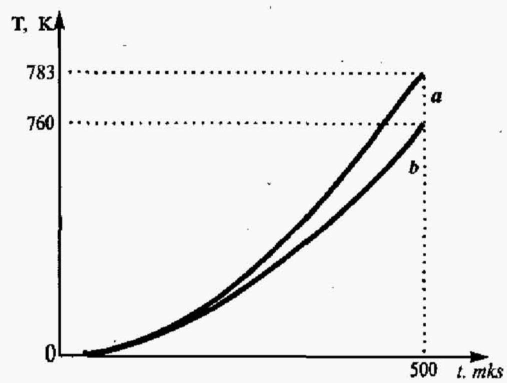

Figure 2. Calculated values of IC heating at HEMP duration 5 mks: a) without taking into account temperature dependence of thermal conductivity of the semiconductor; b) In view of semiconductor thermal conductivity dependence on temperature

References

[1]. Zhuravliov V., Alexeev V. Influence of electromagnetic impulses on degradation of ICs. // XXVth General Assembly of the International Union of Radioscience. Lille, France. - 1996. – p.258.

[2]. Bonch-Bruevich V.L., Kalashnikov S.G. Physics of semiconductors. Nauka, 1990. – 688 p.

[3]. Dzhaksimov E. Elements of the theory photon and phonon effects in semiconductors. - Tashkent: Fan, 1979. - 175p.