A method for extraction of power dissipating sources from interferometric thermal mapping measurements

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Abstract

We report on a method for the extraction of power dissipation sources inside semiconductor devices from laser-interferometry thermal mapping measurements. The two-dimensional power dissipation density is calculated from the time and space derivative of the measured optical phase shift. The method is applied to the analysis of an electrostatic discharge (ESD) protection diode. The extracted spatial and temporal behavior of the power dissipation density reflects well the expected device behavior. The method supplies the important information on the nanosecond to microsecond thermal behavior of ESD protection and power devices working under high current densities.

1. Introduction

Experimental access to internal parameters of semiconductor devices as temperature, power dissipation or current density is important for the understanding of device reliability physics. Temperature monitoring is especially important in power and electrostatic discharge (ESD) protection devices [1] - [3]. These devices operate at high current densities and/or high blocking voltages.

Backside laser interferometry is a useful tool for nanosecond - time resolved characterization of devices subjected to short high current pulses [4]. It is based on monitoring of the optical phase changes caused by temperature - induced variations in the semiconductor refractive index. An infrared non-absorbing probe laser beam is used for the device probing from the polished backside. The dynamics of hot spots, lateral thermal energy, free carrier and current flow distribution have been investigated in CMOS [5] and smart power technology ESD protection devices (PDs) [4]. A good agreement between the experiment and device simulation has been found [6]. In the case of a dominant thermal contribution, the phase signal \( \Delta \phi \) is found to be directly proportional to the two-dimensional thermal energy density \( E_{2D} \) inside the device [7]:

\[
\Delta \phi( x, y, t ) = \frac{4\pi}{\lambda} \frac{dn}{dT} E_{2D}( x, y, t )
\]  

(1)

where \( \lambda \) is the laser wavelength, \( c_V \) the volume thermal capacity, \( dn/dT \) the temperature coefficient of the refractive index (or thermo-optical coefficient [8]) and \( x, y \) the lateral coordinates. The material parameters \( c_V \) and \( dn/dT \) are considered to be temperature-independent. The energy density \( E_{2D} \) is a quantity, which depends on the power dissipation density and on its spatial and temporal behavior. For a dominant Joule heat, the power dissipation density is a product of current density and electric field. These quantities directly reflect the internal device behavior.

In this paper we present a method for extraction of two-dimensional power dissipation density from the backside laser interferometric thermal mapping experiments. The method is based on the integration of the thermal diffusion equation. The method is applied to the analysis of ESD protection diodes working in the avalanche regime.

2. Extraction method

The phase shift of the laser beam is proportional to the integral of the temperature change \( \Delta T(x,y,z,t) \) along the laser beam path:

\[
\Delta \phi( x, y, t ) = \frac{4\pi}{\lambda} \frac{dn}{dT} \int_0^L \Delta T( x, y, z, t ) dz
\]  

(2)

where the integration is performed along the beam path through the substrate of the thickness \( L \) (see the inset of Fig. 1a). More details on the measurement principle and the used approximations can be found in [4], [7]. In order to express the phase shift in terms of the power-dissipating sources, let us consider the thermal diffusion equation, which can be expressed in the following form [9]:

\[
\frac{\partial E_{2D}}{\partial t} = \nabla \cdot ( k \nabla E_{2D}) + \rho \omega
\]

where \( k \) is the thermal conductivity, \( \rho \) the density of the device, and \( \omega \) the power dissipation per unit volume.
\[
\frac{\partial \Delta T(x, y, z,t)}{\partial t} = c_v \left( \frac{\partial^2 \Delta T}{\partial x^2} + \frac{\partial^2 \Delta T}{\partial y^2} + \frac{\partial^2 \Delta T}{\partial z^2} \right) \tag{3}
\]

where \( P_{2D}(x, y, z,t) \) is the 3-dimensional power dissipation density, and \( \kappa \) is the thermal conductivity. For the sake of simplicity, \( \kappa \) is considered to be temperature independent. Integration of (3) over the z-coordinate gives:

\[
\frac{\partial \Delta \phi(x, y, t)}{\partial t} = \frac{4\pi}{\lambda c_v} \frac{dn}{dT} P_{2D}(x, y, t)
\]

\[
+ \frac{\kappa}{c_v} \left( \frac{\partial^2 \Delta \phi(x, y, t)}{\partial x^2} + \frac{\partial^2 \Delta \phi(x, y, t)}{\partial y^2} \right)
\]

\[
+ \frac{4\pi}{\lambda c_v} \frac{dn}{dT} \int_0^L \left( \frac{\partial^2 \Delta T(x, y, z,t)}{\partial z^2} \right) dz
\]

The integral term in (4) can be neglected \((j \rightarrow 0 \text{ for } z=L \text{ and } z=0)\) in the particular device studied. The final expression for \( P_{2D} \) therefore reads:

\[
P_{2D}(x, y, t) = \int_0^L P_{3D}(x, y, z, t) dz.
\tag{5}
\]

The studied diode is a smart power technology ESD protection device operating in avalanche mode [4]. The device is prepared on a lightly doped n+ epitaxial layer, which is grown on a p- substrate. A n+ sinker and p+ region is employed as contact on the cathode and anode side, respectively. The length/width of the diode active area is \( L=33\mu m \), and the time resolution is 3ns. The scanning step is chosen to 1µm in both lateral directions.

The previous analysis of the same device, using the measurements of the total space integral of the phase shift, indicates that the heat transfer from silicon to the top device layers (metallization, SiO2) can be neglected in the time scale studied [7]. As a result, the last term in (4) can be neglected. This justifies the use of (6) in the \( P_{2D} \) analysis.

In order to calculate the time and space derivatives using (6), the rough data were first digitally filtered by a median and moving average filtering. The smoothing is also applied on the calculated first and second space derivatives of the phase shift.

3. Experiments and methods

The studied diode is a smart power technology ESD protection device operating in avalanche mode [4]. The device is prepared on a lightly doped n+ epitaxial layer, which is grown on a p- substrate. A n+ sinker and p+ region is employed as contact on the cathode and anode side, respectively. The length/width of the diode active area is \( L=33\mu m \), and the time resolution is 3ns. The scanning step is chosen to 1µm in both lateral directions.

The spatial extent of the heat source (with a homogeneous heat distribution) is larger than about triple of the diffusion length. The diffusion length in silicon is \( L_{th} = 3\mu m(100ns/t) \), where \( t \) is the time duration of the heating [10]).

At this point we notice a difference between the thermal energy density \( E_{2D} \) and the power dissipation density \( P_{2D} \). \( E_{2D} \) at a particular position \( \{x,y\} \) is directly related to the local phase shift via (1). \( E_{2D} \) is the energy stored in the silicon volume defined by the laser beam [7]. On the other hand for calculation of \( P_{2D} \) at point \( \{x,y\} \), phase shift measurements in the neighborhood of \( \{x,y\} \) in the x- and y- directions have to be available. Therefore \( P_{2D} \) is not a simple time derivative of \( E_{2D} \) (or phase shift). \( P_{2D} = \frac{\partial E_{2D}}{\partial t} \) holds only e.g. in the case of large devices with a homogeneous heat distribution during the heating pulse (see above).

The optical measurements were performed with an automated scanning setup [4]. The temperature induced-changes in the phase shift are detected by a heterodyne interferometer using a probe beam with \( \lambda=1.3 \mu m \). The optical spatial resolution is 1.5µm and the time resolution is 3ns. The scanning step is chosen to 1µm in both lateral directions.

In order to calculate the time and space derivatives using (6), the rough data were first digitally filtered by a median and moving average filtering. The smoothing is also applied on the calculated first and second space derivatives of the phase shift.

4. Results

Figure 1a shows the evolution of the phase distribution along the device length during and after the heating pulse. During the stress pulse \( (t=150ns) \) the phase shift distribution is homogeneous over the whole
anode length. At the edges of the structure the phase shift drops to zero over a distance nearly $2L_{TH}$. The slightly higher phase shift on the cathode side edge of the anode is caused by the effect of the distributed resistance of the buried layer. The potential drop in the pn junction is higher there compared to the opposite side. This leads to higher power dissipation on the cathode side edge of the anode. Long after the pulse end the distribution smears out and exhibits a peak, due to the heat diffusion to sides (see the $\Delta \varphi$ curve at $t=1\mu s$ marked with the dotted line in Fig. 1a). The phase distribution along the device width is almost homogeneous in the active area during the heating (Fig. 1b). After the heating pulse, the distribution at the edges smears out similarly as in Fig. 1a. However the phase shift in the region near the middle of the device ($-25\mu m<y<25\mu m$) is nearly flat also at higher times ($t<1\mu s$), even if the phase amplitude decreases. This is because the device width is large compared to $3L_{TH}$ at $t=1\mu s$ ($\approx 28\mu m$, see Part 2).

Figure 2 shows the extracted power dissipation density $P_{2D}$ along the x-axis for two times during and two times after the pulse. The distributions are taken at $y=0$. The spatial derivative term $\partial^2 \Delta \varphi / \partial y^2$ in (6) was neglected. This is possible as the phase distribution in the $y$-direction at $y=0$ is nearly flat (see Fig. 1b). The extracted power density during the pulse is well confined and nearly constant in the anode region. The extracted value of $P_{2D} = 19\pm 2$ mW/µm$^2$ in the active region is consistent with the value calculated from the ratio of the electrical dissipated power (62.4W) and the device area (3300µm$^2$). The higher power dissipation at the cathode side of the anode cannot be resolved, as it is masked by the ripples. They originate from the not yet optimized smoothing and numerical derivation procedures. We also remark that the non-zero $P_{2D}$, observed in the region between the anode and cathode, indicates the power dissipation in the buried layer resistance. This dissipation can already be seen in the phase shift data (see the non-zero $\Delta \varphi$ in the region $40\mu m<x<60\mu m$ at $t=150$ns in Fig. 1a).

After the pulse end ($t=200$ns and 500ns), $P_{2D}$ is zero as expected. This demonstrates the correctness of the used approximations. The ripples in the distribution at $t=200$ns near $x=0\mu m$ and $x=40\mu m$ (see Fig. 2) are caused by the above-mentioned non-optimization in the numerical derivation.

Figure 3 explains how the distributions in Fig. 2 are produced. The time derivative (TD) and space derivative (SD) terms from (6) are here plotted at one time instant during ($t=100$ns, Fig. 3a) and one after ($t=200$ns, Fig. 3b) the pulse. The right hand side of (6) is expressed as: $P_{2D} = TD - SD$. During the pulse the difference between these two terms gives rise to a non-zero $P_{2D}$. After the pulse the two terms equalize as expected (i.e. $P_{2D} = 0$). Figure 4 summarizes the measured $\Delta \varphi$ and extracted $P_{2D}$ evolutions in the middle of the device (point $x=20\mu m$, $y=0\mu m$). The phase shift, representing $E_{2D}$, linearly increases during the pulse. After the pulse end, it decays due to the heat transfer to sides. $P_{2D}$ during the pulse is nearly constant, and can be approximated as $P_{2D} = \alpha E_{2D} / \alpha t$. After the pulse $P_{2D}$ drops abruptly down as expected. The second derivative term in (6) cannot be neglected anymore. The large noise in $P_{2D}$ data is caused by a small step (10ns) in the time derivation calculation. The slightly negative $P_{2D}$ after the pulse is caused by the already-mentioned non-optimized numerical derivation procedure.

Figure 1. Phase distribution along the device length (a) and width (b) during and after the stress pulse. The device cross section with indicated laser beam is schematically given in (a).

Figure 2. Extracted $P_{2D}$ along the device length during and after the stress pulse: $dn/dT=1.9\times10^4$ K$^{-1}$ [8], $c_v = 1.63\times10^6$ J/K/m$^3$ and $\kappa = 150$ W/K/m [11].
Figure 3. Extracted time (TD) and space derivative (SD) contributions to $P_{2D}$ as a function of position along the device length for a time instant during (a) and after (b) the stress pulse.

Figure 4. Measured phase shift (a) and extracted $P_{2D}$ (b) as a function of time.

5. Conclusions

A method for the extraction of two-dimensional power dissipation density $P_{2D}$ from backside interferometric thermal mapping measurements has been proposed. $P_{2D}$ is calculated from the time and spatial derivative of the measured phase shift. For the extraction of $P_{2D}$ at a certain lateral position, the phase shift data in a finite region have to be evaluated. This is different than the calculation of the thermal energy density $E_{2D}$, which is directly proportional to the local phase shift. The space distribution and time evolution of $P_{2D}$ have been analyzed on a diode ESD protection structure. The extracted $P_{2D}$ in this device with homogeneous power dissipation agrees well with the expected value. The region with the dominant power dissipation is well confined within the anode area. The method can be used for the analysis of power dissipation sources in ESD protection and power devices. These devices often exhibit a complex spatial and dynamic behavior, e.g. inhomogeneous current flow or formation of moving current filaments. The method thus allows a quantitative analysis of such phenomena.

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6. References