Thermal Imaging at Multiple Time Instants for Study of Self-Heating and ESD Phenomena

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A 2D backside transient interferometric mapping (TIM) method for nanosecond thermal energy imaging at multiple time instants during a single stress event is introduced. The method is based on fringe interferometry and the interferograms are analyzed using the Fast Fourier Transform technique. The method is applied to investigate moving current filaments in smart power DMOS transistors and in electrostatic discharge (ESD) protection devices exhibiting non-repeatable triggering behavior under ESD-like stress. The method additionally allows the extraction of instantaneous 2D power dissipation density (P_{2D}), which represents the current density distribution in the devices.

Introduction

Protection against electrostatic discharge (ESD) is an important requirement in automotive electronics [1]. For optimization of ESD protection devices (PDs) and for verification of device simulation models it is important to have an experimental access to the internal device behavior. Since self-heating is the main device failure cause [2], the temperature monitoring is especially important in device inspection.

Recently a 2D backside transient interferometric mapping (TIM) technique based on fringe interferometry has been introduced for ns thermal energy imaging at single time instants during a single stress event [3]. However, measurements of devices with complex unrepeatable current filament dynamics are time consuming to perform. An extended version of the 2D TIM method suitable for imaging at two time instants during a single stress event has been therefore developed [4], which overcomes the above limitation. In this article, smart power technology high power DMOS [5] and ESD protection devices [6] developed for automotive applications are investigated by this method. In addition, the current density distribution in the devices is extracted from the measurements.

Experimental Setup and Theory

The backside 2D TIM technique is based on the thermo-optical and plasma-optical effect. During the electrical pulse, the temperature and the free carrier density variation cause a change in the optical length of the laser beam. The optical path difference is measured in a Michelson interferometer, see Fig. 1. For imaging at two time instants, two orthogonally polarized laser beams produced by two high energy pulsed laser sources (λ = 1.3 µm, 5 ns pulses), combined by a polarizing beam splitter cube (PBS1) are led into the Michelson interferometer. The parallel beams reflected from the device (DUT) (see detail on the right in Fig. 1) and from the reference mirror (M) are split according to their polarization (PBS2) and create the interference fringe patterns on two infrared (IR) cameras. The laser pulse positions relative to the stress pulse can be chosen independently. The image and waveform acquisition is synchronized and computer controlled.

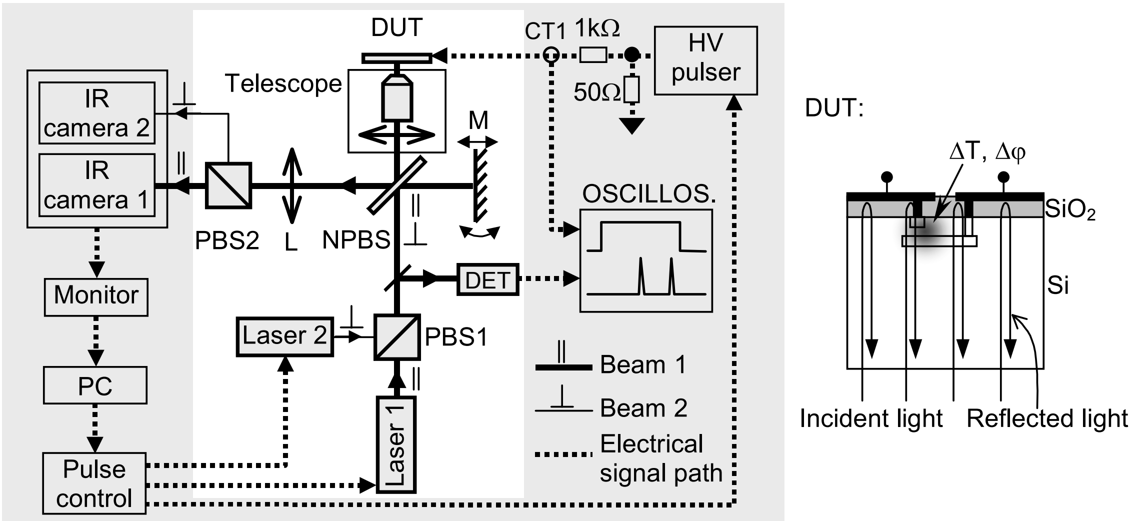

Fig. 1: Schematic drawing of the setup: PBS – polarizing beam splitter, NPBS – non-polarizing beam splitter, M – mirror, L – lens, DET – optical detector, CT1 – current probe, DUT – device under test (after [4]). On the right side the cross section of a DUT, the probe laser beam and the heat source ΔT is depicted.

The temperature-related phase distribution in the device at a particular time instant is extracted using a FFT-based method [7]. For elimination of the phase profile arising from the device the reference phase related to the interferogram without heating is subtracted. This removes also the phase tilt introduced by the reference mirror. The phase calculation results in phase modulo 2π, and the unwrapping is necessary. For unwrapping the pixel queue method or the minimum spanning three method are performed [8], [9]. Before the unwrapping is done, a pre-processing procedure is developed [7].

As two images during a single pulse are possible to record, the method allows extraction of the instantaneous 2D power dissipation density P_{2D}, which represents the current density distribution in the devices. Neglecting the heat transfer to the top device layers (normal component of the heat flow vector), P_{2D} is given by [6]:

$$P_{2D}(x,y,t) = \lambda\left(4\pi\frac{dn}{dT}\right)^{-1}\left(c_V\frac{\partial\varphi(x,y,t)}{\partial t} - \kappa\frac{\partial^2\varphi(x,y,t)}{\partial x^2} - \kappa\frac{\partial^2\varphi(x,y,t)}{\partial y^2}\right) \quad (1)$$

where λ is the laser beam wavelength, dn/dT is the temperature coefficient of the refractive index, c_V is the volume specific heat, $\varphi(x,y,t)$ is the measured phase shift, κ is the thermal conductivity, x, y and t are the spatial coordinates and time, respectively. The time derivative in Eq. (1) is approximated using the phase difference between two images $\varphi(x,y,t)$ and $\varphi(x,y,t-\Delta t)$ recorded during the same ESD pulse at times t and $t-\Delta t$, respectively. The value of Δt = 30 ns is a good compromise taking into account the phase and space resolution of the setup.

Results

The method is applied to the study of moving current filaments in ESD protection devices and DMOSes during a bipolar snapback mode where the current distribution in the device is strongly inhomogeneous. The backside IR image of the ESD PD is shown in Fig. 2 (a) and its cross section in Fig. 2 (f). Figures 2 (b) – (e) and (g) – (j) show the measured phase images and the extracted P_{2D} at four time instants, respectively. Due to the negative differential resistance a current filament, represented by a spatially localized P_{2D}, is formed in the middle of the device, see Fig. 2 (g). Later, due to the reduction of the impact ionization coefficient with increasing temperature, the filament starts to move towards a cooler region (to the corner) of the device, see Fig. 2 (h). When the filament reaches the corner, it is “reflected” back (Fig. 2 (i)) and moves again to the middle and toward the opposite corner of the device (Fig. 2 (j)). The initial direction (right or left) of the movement is random. The current filament amplitude is about 30 mW/μm^2, which is consistent with the results obtained previously using the time-consuming scanning TIM method [10].

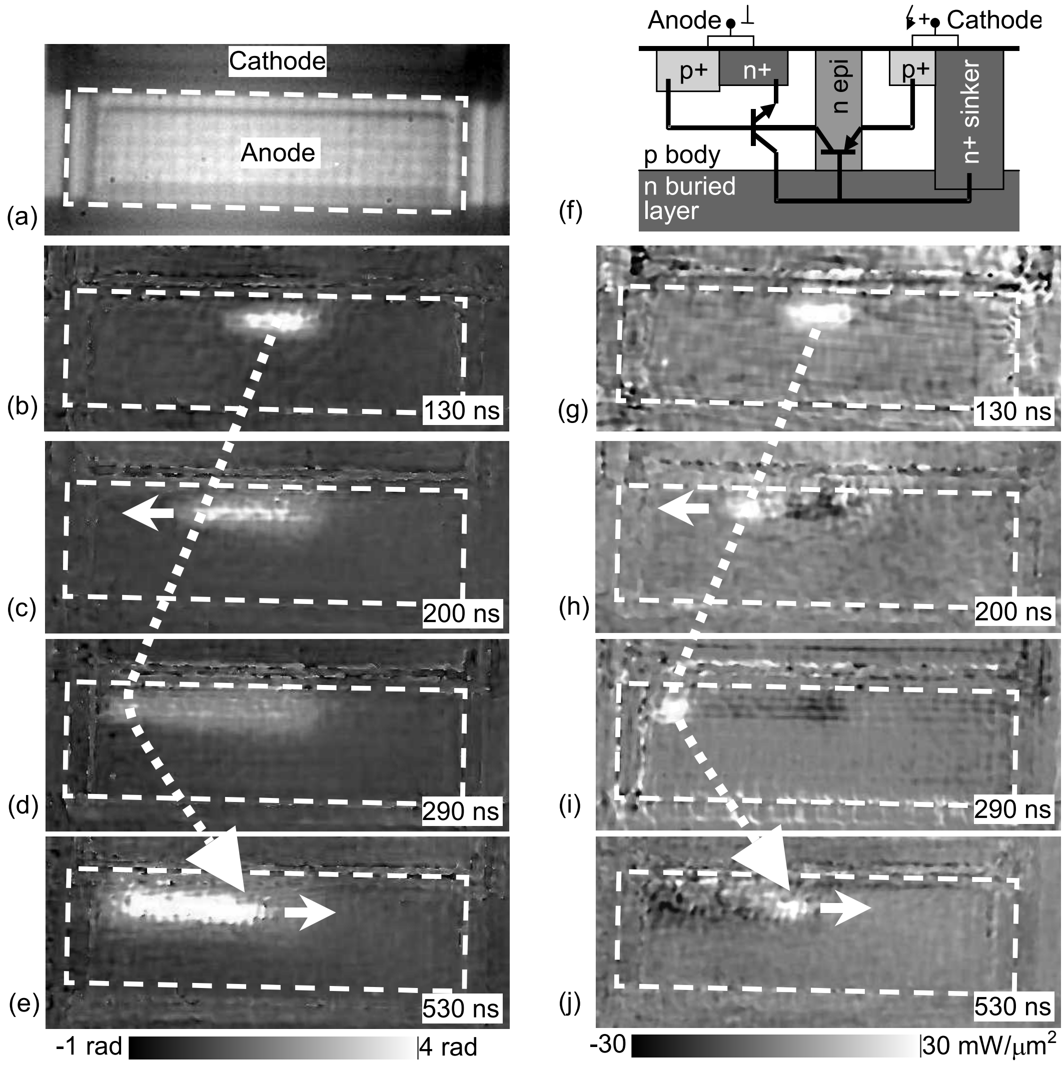

Fig. 2: (a) Backside IR image of the ESD PD and (f) device cross section. (b) – (e) Phase shift distribution $\varphi(x,y,t)$ in the ESD PD at four time instants during current pulses of 0.25 A, 600 ns duration. The heating is displayed by light color. (g) – (j) show the P_{2D}, representing the current filament position. The dashed arrow and the small white arrows denote the movement direction (after [4]).

The backside IR image of the DMOS device is shown in Fig. 3 (a) and its cross section in Fig. 3 (b). At snap back, when the parasitic bipolar transistor (see Fig. 3 (b)) of the DMOS turns on, a few cells take over the current and localized current filaments are formed along the source field termination. With time the filaments penetrate into cooler regions. The trigger position, number of the filaments, and direction of their movement vary randomly and non-repeatedly from pulse to pulse [4], [5].

In order to localize the active cell at a particular time instant in the DMOS, the P_{2D} is necessary to extract. For this the two imaging laser beams were positioned at time instants 120 ns and 150 ns, see Figs. 3 (c), (d). The P_{2D} calculated by Eq. (1) corresponding to $t = 150$ ns is shown in Fig. 3 (e). At this particular case, DMOS cells marked by the circles inside of the source field are active and there are no more active cells along the termination line.

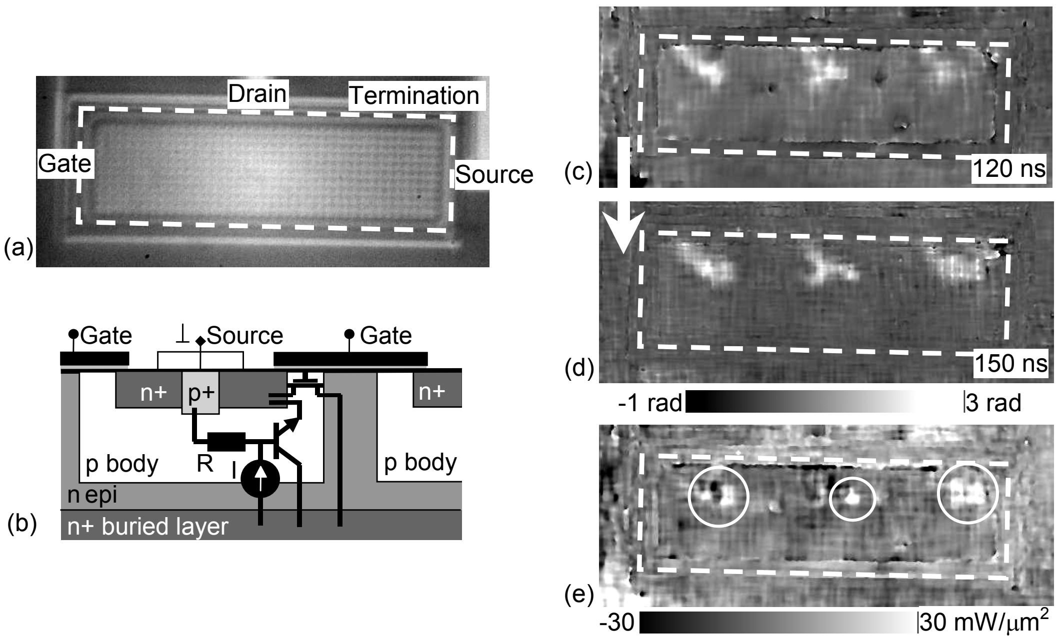

Fig. 3: (a) Backside IR image of the vertical DMOS, (b) device cross section. (c, d) Phase shift distribution in the DMOS at 120 ns and 150 ns during a 3 A, 250 ns stress pulse and (e) corresponding P_{2D} (after [4]).

Conclusion

With the presented method, the position and direction of the filament movement can unambiguously be extracted from few single-shot measurements. Using the two-time-instant measurement the instantaneous power dissipation density can be obtained. This allows investigation of current dynamics in devices exhibiting complex unrepeatable behavior, which is not possible by any other method. The method has a potential for time-efficient studies of destructive phenomena in semiconductor devices including thermal run-away effects in the ns to ms time range and study of surface displacement of MEMS, bio-membranes, sensors and microfuidics.

Acknowledgements

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