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Temperature mapping by μ-Raman spectroscopy over cross-section area of power diode in forward biased conditions

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ABSTRACT

It has been demonstrated that high power devices like power diodes and IGBTs (Insulated Gate Bipolar Transistors) could remain functional after cross section. This has opened a field of possibilities for the characterization of distribution of physical quantities over vertical cross-sections of power semiconductor devices. In this paper, we used the Raman spectroscopy technique to perform the mapping of temperature distribution over the cross section area of a forward biased power PIN diode. As the mechanical stresses lead to shift the Raman peak, for accurate measurements in strained structures, it is necessary to deconvolute the influence of stress and temperature on Raman shift to measure temperature. Another solution consists in measuring the Full Width at Half Maximum (FWHM) of the silicon related Raman peak. This parameter depends only on the temperature and the crystalline quality of material. By this way, it is possible to measure the temperature accurately without any artifact due to the stress. Using this method, we have measured the temperature distribution over a vertical cross section of a power diode in forward bias conditions and strained by its packaging. The residual stress in the chip cross section was also estimated at room temperature in order to validate the FWHM choice for temperature calibration.

1. Introduction

It is well known that semiconductor power devices are subjected to very high electrical and thermal stress levels which may affect their reliability. Thus, characterizations of current densities and temperature distributions within the bulk of power devices are required for the physics of failure analysis. These distributions are highly distributed inside the semiconductor devices during operation. This is not only due to the electro-thermal coupling but also to the spatial bond-wire contact configuration on the top-metal. Conventionally, infrared thermal mapping on the top surface of the chip is usually performed [1]. Despite some disturbances caused by bond wires, this analysis provides information on surface temperature distribution only. However, such top surface thermal mapping does not provide accurate information on the vertical distributions of neither temperature nor current flow inside the bulk.

In our knowledge, only few papers deal with electrical or thermal characterizations inside the bulk of power devices. Deboy et al. [2] have realized measurements of carrier concentrations and temperature gradients using IR laser deflection on low power insulated-gate bipolar transistor (IGBT). However, this technique requires the exact knowledge of the derivative of the refractive index on carrier concentration and temperature. Concerning measurements on device cross-sections, Doukkali et al. [3] and Susumu et al. [4] have carried out measurements on electrical or thermal mapping but only on integrated circuit devices. Such investigations have not yet been reported on very high power devices such as power diodes or IGBTs.

Recently, we demonstrated that high power devices like diodes and IGBTs could remain functional after cross section [5]. In case of the power diode, for example, it has been shown that the cross-section has a relatively low impact in the threshold voltage on the forward characteristics and affects slightly the slope of the current–density/voltage (J–V) curve. (Fig. 1). In this case, among the possible hypotheses, we can assume that, under high injection conditions, edge effects result in a disturbance of the stored charge near the cross-section and thus in a loss of conductivity modulation and finally, in an increase in forward voltage drop.

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In a first step, the general objective is to show the feasibility of such measurements. However, in a second step, we must correct the edge effects disturbance in the measurements in order to take them into account. This last point remains to be done in further works.

This new characterization possibility opens a wide field of investigation for high power semiconductor devices if cross-section perturbation effects can be corrected. Large possibilities of in situ characterizations can be applied to measure internal quantities such as the temperature distribution. In the continuity of the work presented in [5], we propose in this paper to investigate the suitability of μ-Raman method to characterize the vertical thermal distribution within a cross-section of a power diode in forward bias conditions.

Raman spectroscopy is commonly used in microelectronics in order to determine stress or temperature distribution in devices [6–7]. Its possibilities have been demonstrated in terms of spatial resolution and precision of measurements. Raman is a spectroscopic technique based on the inelastic scattering of a monochromatic light exciting a material. Frequency of the scattered light is shifted up or down in comparison with the original monochromatic frequency, which is called the Raman effect. This shift provides information about vibrational, rotational and other low frequency transitions in material which depend directly on the material temperature and/or the strain state. More precisely, the material temperature induces shift and FWHM variation of the scattered photons related peak while stresses only shift the peak [8]. For strained material, it is preferable to calibrate the temperature using the FWHM of the Raman peak because this parameter is independent of strains inside the material unlike Raman shift which depends also on the strain state and introduces errors in the measurements. However, the position measurements offer more precise results than FWHM because the phenomenon is more pronounced. For a 100 °C heating (20–120 °C) in silicon, we observe a 2 cm^{-1} shift and 0.8 cm^{-1} broadening of the Raman silicon line. In the following, we present the temperature distribution measurements using μ-Raman spectroscopy and measuring FWHM of the scattered light on a forward biased power diode cross-section. We used a confocal microscope for laser focalization and light analysis. In this condition, Raman spectroscopy offers high spatial resolution (<1 μm) and also permits depth analysis. This configuration is very interesting for the study of micrometric structure involved in die synthesis.

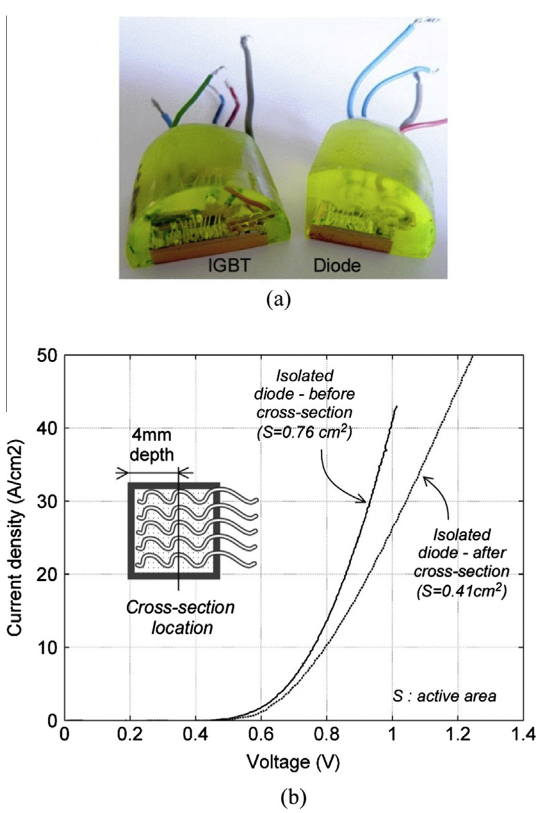

Fig. 1. Device cross-sections (a) and power diode steady-on state characteristics at 25 °C before and after cross-section (b) [5].

2. Raman thermal characterization and discussion

A LabRAM HR800 micro-Raman spectrometer commercialized by Jobin Yvon was used to obtain the Raman spectra of the device at an excitation wavelength of 632 nm. The spectrometer operates in backscattering geometry and uses a grating of 2400 lines mm^{-1}. Different types of lenses with various numerical apertures were used to collect the backscattering light. Their characteristics are summarized in Table 1. Note that the microscope objective numerical aperture (NA) describes the lens ability to collect scattered light from the focused laser spot. The bigger the numerical aperture, the higher the light is collected. The laser focus size is also estimated. It is function of the excitation laser wavelength (λ) and the numerical aperture. The radius of the laser focus is given by [9]:

$$r = 0.61 \times \frac{\lambda}{NA}$$

Laser focus radii of each optical combination are also listed in Table 1. These radii represent the physical spatial resolution limit for each optical mounting. Our Raman system is coupled to a confocal microscope. This implies that the light emitted from the sample is spatially selected in vertical scale (z) by a confocal pinhole. The smaller the pinhole the higher the spatial vertical resolution permitting a surface measurement of the temperature. In this system the pinhole is coupled to the entrance slit of the spectrometer. This explains why the confocal pinhole changes the spectral resolution. Confocal pinhole diameters and the spectral resolutions corresponding use in this study are also reported in Table 1. The laser power irradiating the sample was measured directly by an optical powermeter. The power was maintained at 10 mW. For mapping measurements, the sample is fixed on a motor driven two-dimension stage x, y. The stage is automatically controlled by the micro-Raman spectrometer software.

2.1. Strain measurements

Strain cartography was first measured in unbiased conditions in order to determine the presence of residual stress in the diode structure due to technological process. Knowing the strain states, it is possible to select the most adequate parameter to calibrate the temperature: FWHM or position of the Raman peak. When the temperature or stress changes inside the material, the frequency of the lattice vibrations changes and shifts the Raman frequency. Raman shift measurement does not allow getting precisely the temperature for a strained structure like power module device. The solution consists in measuring the FWHM of the peak which is only temperature dependent [10]. Although the results of the FWHM are acceptable, this method offers less accuracy on temperature measurement than the peak position which explains the interest of these prior measurements.

High power modules are devices made of several materials layers with different properties. These ones are processed by various technologies at different temperatures. During and after processing, mechanical stresses are developed within the structure. These stresses are mostly due to mismatch on thermal expansion coefficients during thermal steps [11]. For power diodes, the packaging process includes wire bonding, solder bumping, chip adhesion to a