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KPFM - Raman spectroscopy coupled technique for the characterization of wide bandgap semiconductor devices

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Abstract. A non-destructive technique for the characterization of the doped regions inside wide bandgap (WBG) semiconductor structures of power devices is presented. It consists in local measurements of the surface potential by Kelvin Probe Force Microscopy (KPFM) coupled to micro-Raman spectroscopy. The combined experiments allow to visualize the space charge extent of the doped region using the near-field mapping and to estimate its dopant concentration using the Raman spectroscopy. The technique has been successfully applied for the characterization of a WBG SiC (silicon carbide) device.

Introduction

Electronic devices based on wide bandgap semiconductors such as 4H-SiC are now widely used in power electronics. The reliability of these power devices is determined by how the strong electric fields present in the semiconductor are handled by device design. Precisely localized doped areas are necessary in order to minimize local electrical field spikes. We present here a non-destructive technique for the characterization of the doped regions in these power devices coupling local measurements of the surface potential by Kelvin Probe Force Microscopy (KPFM) and micro-Raman spectroscopy. The KPFM measurements allow to: i) localize and visualize the extension of the doped regions, ii) identify the location of electric field spikes and iii) characterize the depletion regions at the junction edges or due to doping variations in the semiconductor [1]. Micro-Raman spectroscopy measurements provide additional information on the type the dopants and estimates their concentrations [2].

Experimental details

The near-field KPFM technique is an electrical mode of the atomic force microscope. The operating principle is illustrated in Fig. 1 and it uses an original method [3], [4] which allows the simultaneous measurement of the surface electric potential and the second derivative of the tip/air/surface capacitance. This experimental near-field technique uses a two-step scan (dual-pass mode) for each line in order to allow quantitative surface potential measurements on biased devices [4]. While the first line scan (round trip) is used for the surface topography measurement, during the second scan the tip is lifted-up from the surface at a user-defined height of typically a few tenths of nanometers and follows the previous recorded surface profile while measuring the potential surface profile. An external electronic device (Keysight E5270B) applies the bias voltages to both the sample

under test and the AFM tip during the lift scan, the synchronization with the AFM raster scan being performed using the AFM end-of-line TTL signals [3].

An external digital phase control loop [4] is implemented, enabling to quantitatively measure the surface potential in phase modulation-KPFM mode. The phase shift control loop is based on the measurement of the phase difference $\Delta\phi$ between the cantilever excitation drive signal and the actual cantilever oscillation signal. Within a limited tip-to-surface voltage difference ($V_{tip} - V_{surf}$), the phase shift describes a parabola following [5]:

$$\Delta\phi = -\frac{Q}{2k} \frac{d^2C}{dz^2} (V_{tip} - V_{surf})^2 \quad (1)$$

where V_{surf} is the sample under test surface potential at the tip location and V_{tip} the bias applied to the tip. The term $\frac{Q}{2k} \frac{d^2C}{dz^2}$ is the phase parabola opening with Q the quality factor, k the spring constant of the cantilever and C the tip/air/surface capacitance.

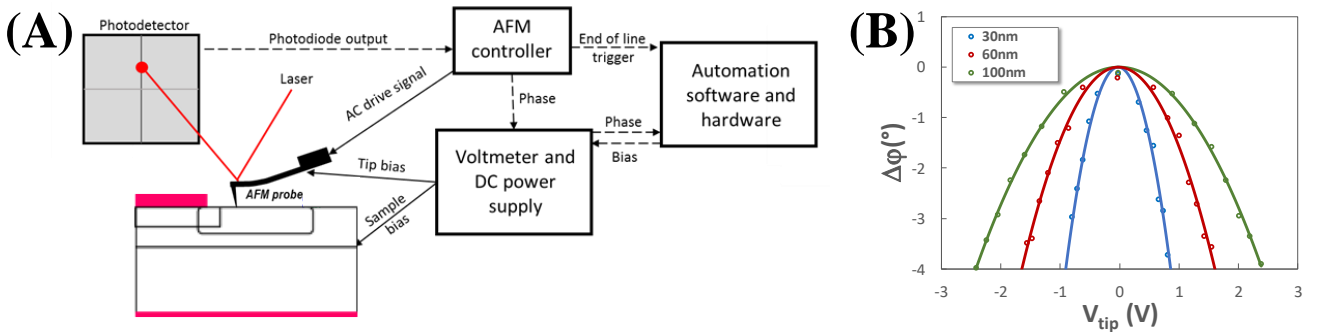


Fig. 1. Schematics of the KPFM setup and illustration of the lift mode (A) and measured phase shift versus tip bias at various lift heights (B).

In this study, the area of interest is the lateral emitter junction periphery of a high voltage (5 kV) 4H-SiC PiN diode. This area, called the Junction Termination Extension (JTE), is designed to avoid the abrupt increase of the electric field at the P⁺ emitter edge. The fabrication process and static electrical characteristics of these 5 kV 4H-SiC PiN diodes are detailed in [6, 7]. The diodes cross-section is shown in Fig. 2A and optical images are presented in Fig 2B. The identification of this area of interest is obtained using KPFM thanks to the variation of the second derivative of the capacitance which gives information on the location of the charges [4].

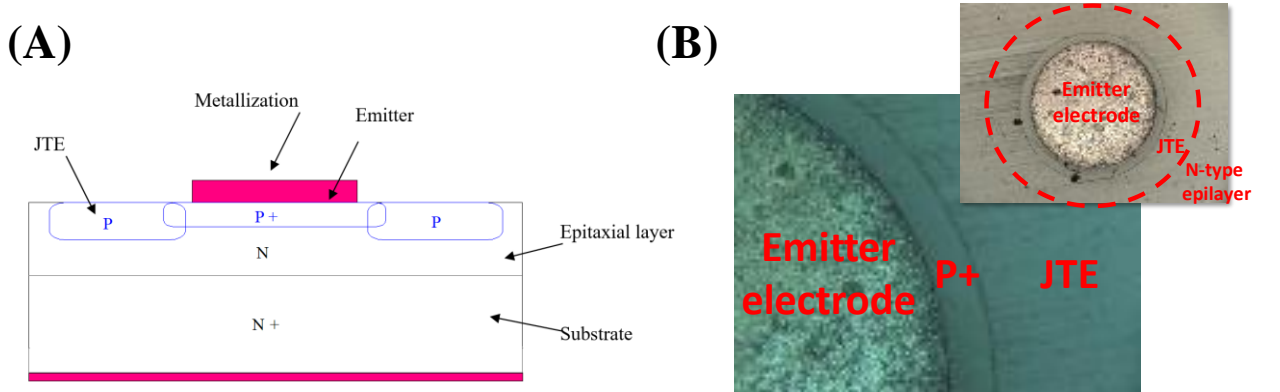


Fig. 2. Structure of the sample with the area of interest of the vertical bipolar PiN diode highlighted (A); Identification of the different device parts on the optical microscope image (B).

Raman spectroscopy was used to measure dopant concentration in specific areas [8]. Compared to conventional techniques such as C-V, SIMS (Secondary Ion Mass Spectrometry) or Hall effect, Raman spectroscopy is a non-contact, non-destructive and easy to implement alternative to investigate doped areas.

Due to its high photon energy, a 325 nm near-UV was selected in order to limit the investigated volume, since the JTE depth is less than 1 μm . The JTE Al doping profile is presented in Fig 3. A

doping concentration plateau between 2 and 3 10^{17} cm^{-3} is obtained from Monte-Carlo simulations and confirmed by SIMS measurements [7].

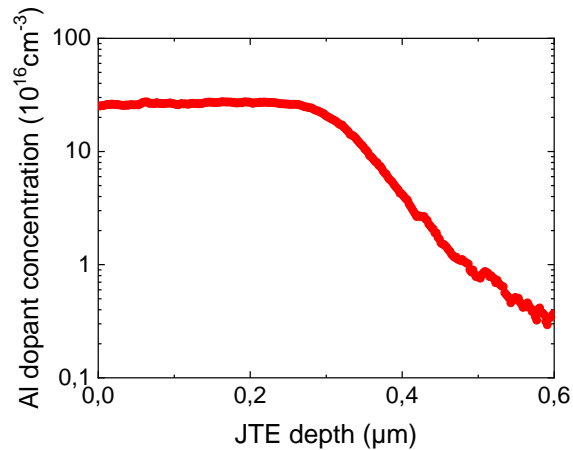


Fig. 3. Doping profile as a function of the JTE depth.

Results and discussion

Using the local capacitance second derivative mapping of the KPFM measurements, the edge of the extension of the JTE implanted junction in reverse bias [6,7] was identified and precisely located as illustrated in Fig. 4. The interface between the JTE (P-doped at $2.5 \times 10^{17} \text{ cm}^{-3}$) and the N-doped epitaxial layer (with a concentration of $1.1 \times 10^{15} \text{ cm}^{-3}$) is visible 250 μm away from the emitter, which corresponds to the expected JTE length. As shown in Fig 4B, the JTE edge detection is performed using a significant variation of approximately 37% of the measured capacitance second derivative in the KPFM scan lines.

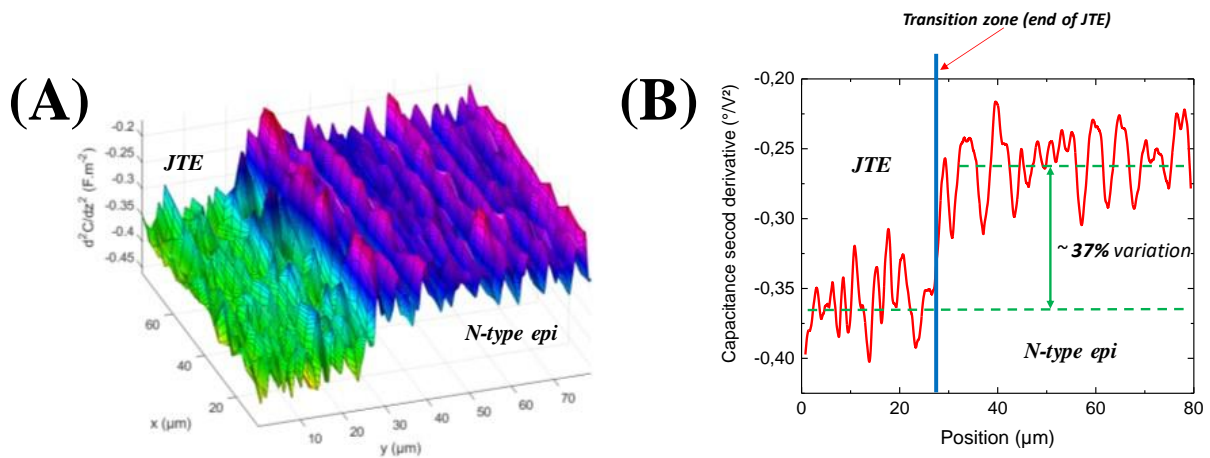


Fig. 4. Mapping of the second derivative of the local capacitance highlighting the edge of the JTE in reverse bias at -45V (A) and capacitive second derivative cross-section showing the step marking the edge of the JTE (B).

Once the location and extent of the JTE are identified, the intensity and the position in Raman shift of the characteristic line of the longitudinal optical plasmons-phonons coupling (LOPC) are used to determine the type and the concentration of dopants in the 4H-SiC device structure [7]. A systematic shift and a decrease of the LOPC peak intensity are found by focusing alternatively at the JTE and at the N-type epilayer surface (Fig 5), confirming the junction interface detected by KPFM.

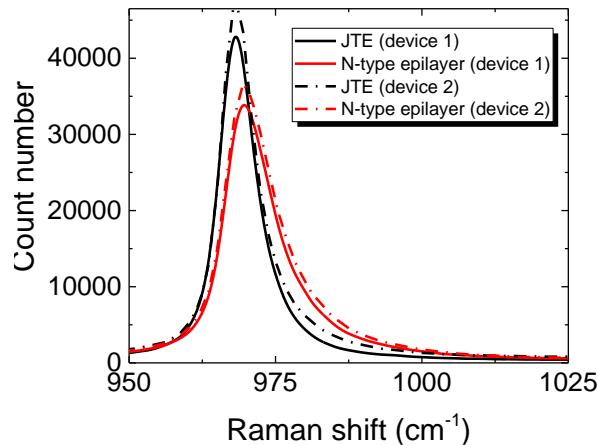


Fig. 5. Raman spectroscopic measurements of the LOPC line (4H-SiC) showing a variation of its position in Raman shift and of its intensity as a function of the doping.

Therefore, by coupling the near-field KPFM measurements with Raman spectroscopy we obtained a non-destructive technique able to identify the exact extent of the JTE region of a SiC diode and we were able to quantify its doping level. Compared to other near-field techniques (such as SCM) the KPFM technique has the advantage of allowing in-situ quantitative surface potential measurements during device operation which can be used for extensive device characterization. This coupled technique can be very useful in reverse engineering of 4H-SiC and other WBG power devices.

Conclusion

A non-destructive technique coupling local measurements of the surface potential by KPFM and micro-Raman spectroscopy was presented. The method was successfully applied to the characterization of the dopants in wide bandgap semiconductor structures. The space charge extent of the JTE region of a wide bandgap SiC diodes could be visualized using the near-field potential mapping, while its dopant concentration could be estimated using Raman spectroscopy.

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