

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

Nicolas BERCU¹, Mihai LAZAR^{1,2}, Olivier SIMONETTI¹, Pierre-Michel ADAM²,
Mélanie BROUILLARD¹, Louis GIRAUDET¹

¹ Laboratoire de Recherche en Nanosciences EA4682 (LRN), Université de Reims
Champagne-Ardenne, 51100 Reims, France

² Lumière, nanomatériaux, nanotechnologies CNRS ERL 7004 (L2n), Université
Technologique de Troyes, France

E-mail: nicolas.bercu@univ-reims.fr

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

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 as a function of the tip/surface height (Fig. 1). 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 $\Delta\varphi$ 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]:

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

where V_{surf} is the device 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.

In this study we localize the area of interest of a high voltage PiN diode power device [6], located on the lateral emitter junction periphery, called Junction Termination Extension (JTE) and which is used to avoid the abrupt increase of the electric field at the P⁺ emitter edge. The identification of this area of interest using KPFM is obtained thanks to the variation of the second derivative of the capacitance which gives information on the location of the charges [4]. The edge of the extension of the JTE implanted junction [6] is located by the KPFM measurements in reverse bias as illustrated Fig. 2B. The interface between the JTE (P-doped) 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 JTE length. Fig 2C presents a variation of approximately 37% of the measured capacitance second derivative at the JTE edge.

Raman spectroscopy is then used to measure doping in areas of interest [7]. Compared to conventional techniques such as C-V, SIMS or Hall effect, Raman spectroscopy represents a non-contact, non-destructive and easy to implement alternative to investigate doped areas.

The 325nm near-UV laser has been chosen from the five different ones of our Raman Horiba commercial equipment in order to limit the investigated volume as the JTE depth is less than 1 μm (the JTE Al doping profile is presented in Fig 3C).

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 dopant 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 3B), confirming the junction interface detected by KPFM. The final paper will detail our results and highlight the aptitude of this non-destructive KPFM-Raman spectroscopy coupled technique in reverse engineering of 4H-SiC and other WBG power devices.

- [1] U. Gysin et al, *Microelectronic Engineering* 160, 18–21 (2016).
- [2] Zongwei Xu et al., *Micromachines* 9, 361 (2018).
- [3] N.B. Bercu et al, *Journal of Microscopy* 267(3), 272-279 (2017).
- [4] G. De Tournadre et al, *J. Appl. Phys.* 119, 125501 (2016).
- [5] P. Girard, *Nanotechnology*, vol. 12, no. 4, pp. 485–490, (2001).
- [6] C. Raynaud et al., June 2004 *Materials Science Forum* 457-460: 1033-1036
- [7] Tao Liu et al, *Crystals* 9, 428 (2019).

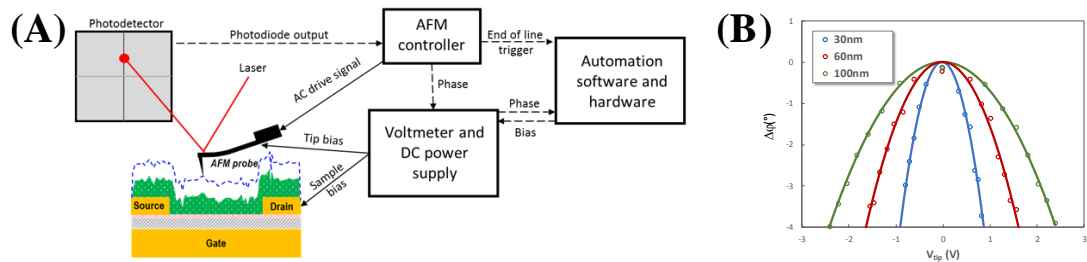


Fig. 1. Schematics of the KPFM setup and illustration of the lift mode (A) and measured phase shift versus tip bias at various lift heights (B).

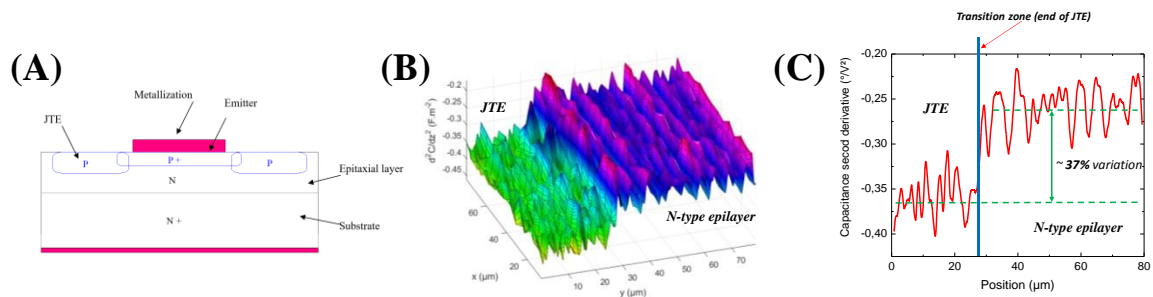


Fig. 2. Structure of the sample with the area of interest of the vertical bipolar PiN diode highlighted (A), mapping of the second derivative of the local capacitance highlighting the edge of the JTE in reverse bias at -45V (B) and capacitive second derivative cross-section showing the step marking the edge of the JTE (C).

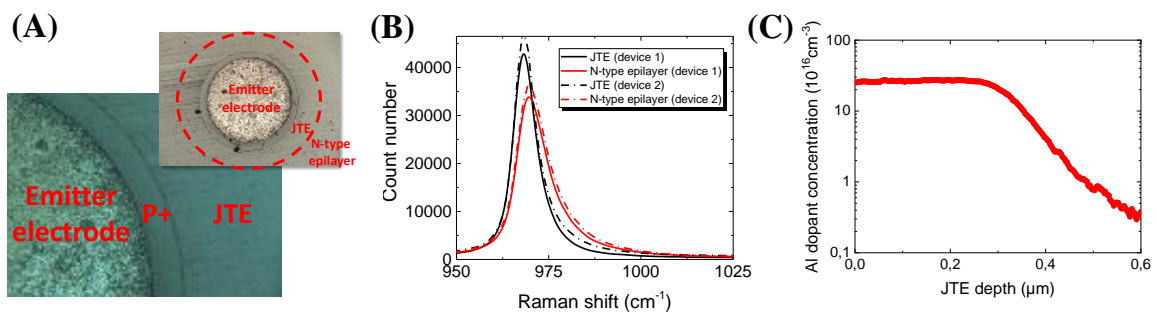


Fig. 3. Identification of the different device parts on the optical microscope image (A), Raman spectroscopic measurements of the LOPC line (4H-SiC) showing a variation of its position in Raman shift and of its intensity as a function of the doping (B) and SIMS doping profile as a function of the JTE depth (C).