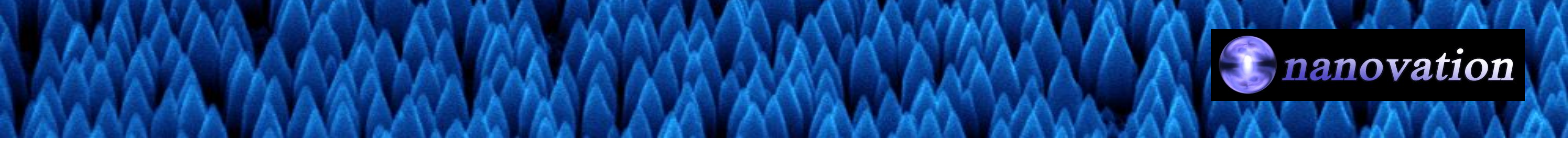

# Investigation of the Prospects of n-$Ga_2O_3$/p-NiO Heterojunctions for Use in Power Electronics

***V. E. Sandana, D. J. Rogers & F. H. Teherani***
*Nanovation, 8 Route de Chevreuse, Châteaufort, 78117, France*
***M. Razeghi***
*Centre for Quantum Devices, ECE Department, Northwestern University, Evanston, Illinois, France*

## *Introduction*

Around a half of the energy of any kind of the world is electricity and > 30% of our electricity supply passes through power electronics components. Nearly all of these currently employ Si-based electronics. These, however, are power-limited and have elevated “on-resistances” for HV operation, and thus very significant resistive losses. To combat these problems, a 2nd generation of PE based on wide-bandgap (WBG) semiconductors (SiC and GaN) has been developed over the past decades. However, the substrates and/or active layers of both materials are produced by energy intensive techniques and are still very expensive. More recently, a very promising 3rd generation of PE based on the WBG Ga2O3 (Eg = 4.9eV), has appeared. This resulted from the discovery of n-type dopability in a material that was previously thought to be an insulator. Consequently, there has been a surge in R&D focused on β-Ga2O3 power switching/ amplification electronics founded on the potential for a much lower on-resistance along with a breakdown (~8MV/cm) and a Baliga’s figure of merit (~1 GW/cm2) which greatly exceed those of Si, GaN or SiC. Since shallow p-type dopants are not available for β-Ga2O3, bipolar homojunction Ga2O3 devices are not possible, however. This work aims to address this problem by integrating n-type β-Ga2O3 with p-type NiO so as to design novel vertical p–n heterojunction diodes. With a bandgap of 3.7 eV, NiO is the complementary p-type oxide of choice through its’ robustness and bandgap uptunability (via Mg alloying).

## *Thin Film Device Stack Growth*

p-i-n device stacks of (a) NiO/MgO/Ga2O3 (bulk) and (b) NiO/MgO/Ga2O3/sapphire were grown by Pulsed Laser Depostion (PLD) using a KrF (248nm) excimer laser.

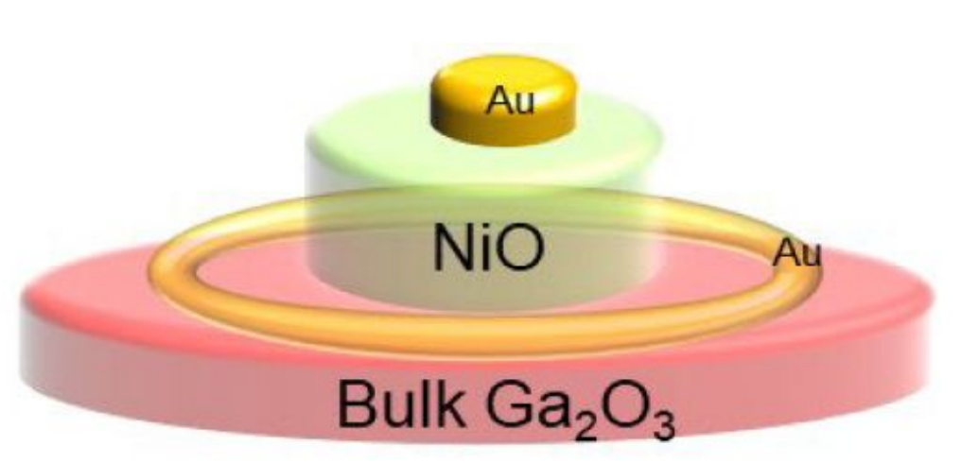

**Figure 1** Schematic of the NiO/bulk $Ga_2O_3$ device mesa structure

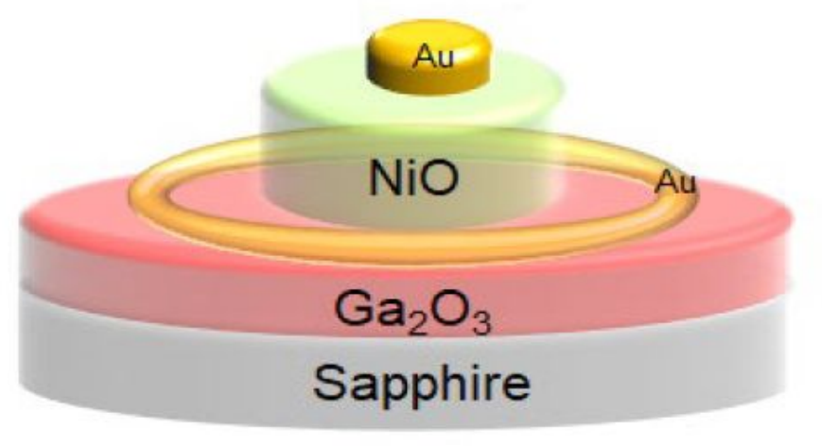

**Figure 2** Schematic of the NiO/Ga2O3/r-sapphire heterojunction.

## *XRD Characterisation*

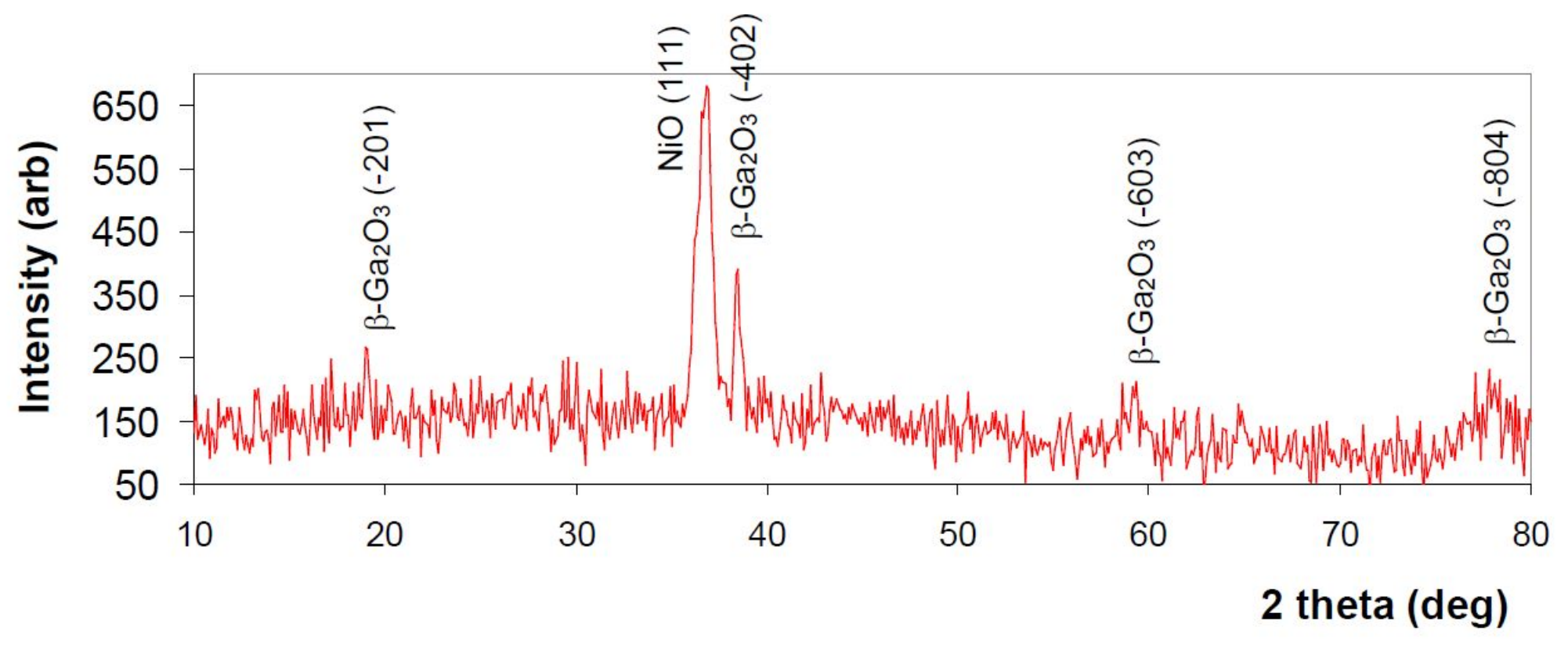

**Figure 4.** XRD 2θ−ω scan for the NiO grown on bulk Ga2O3.

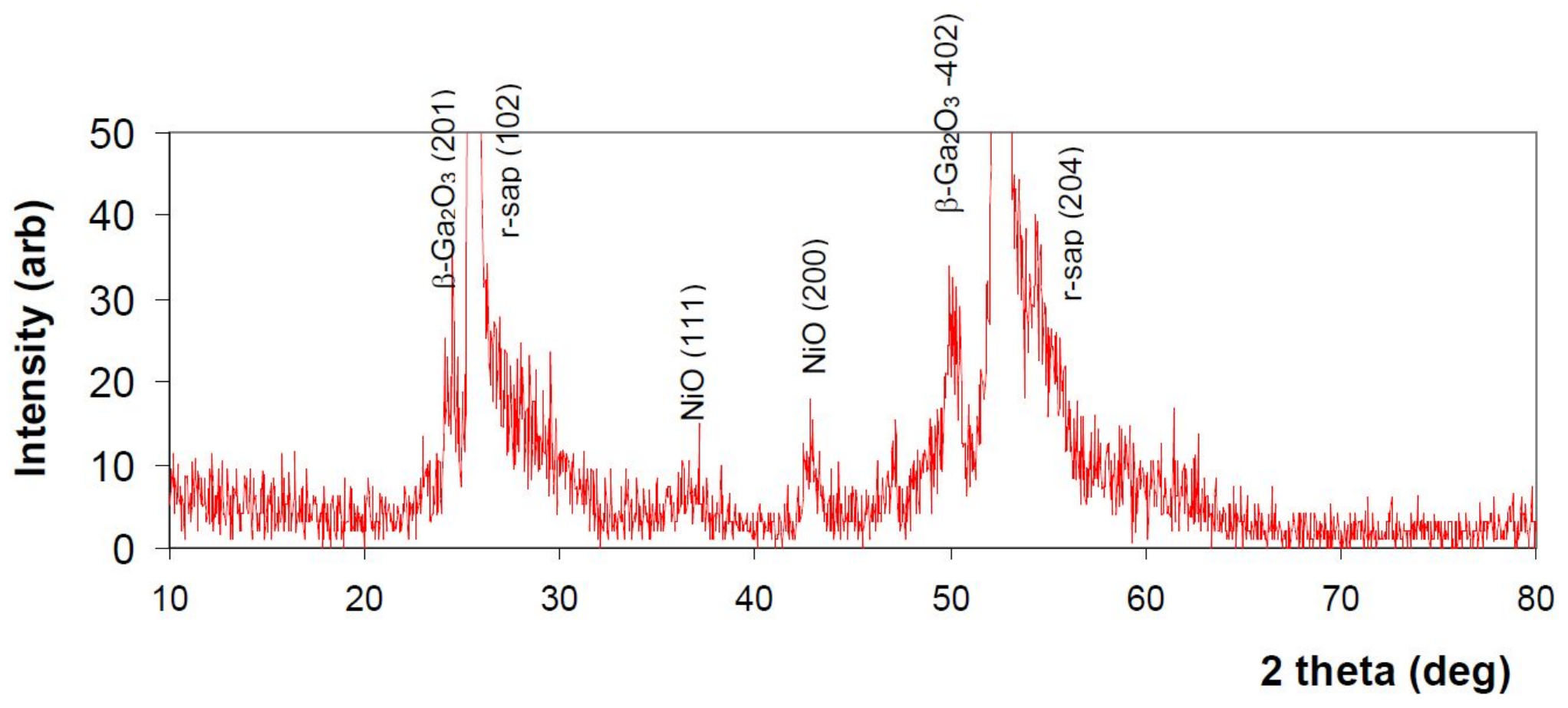

**Figure 9.** XRD 2θ−ω scan for the NiO/$Ga_2O_3$ grown on r-sapphire.

## *IV Characterisation*

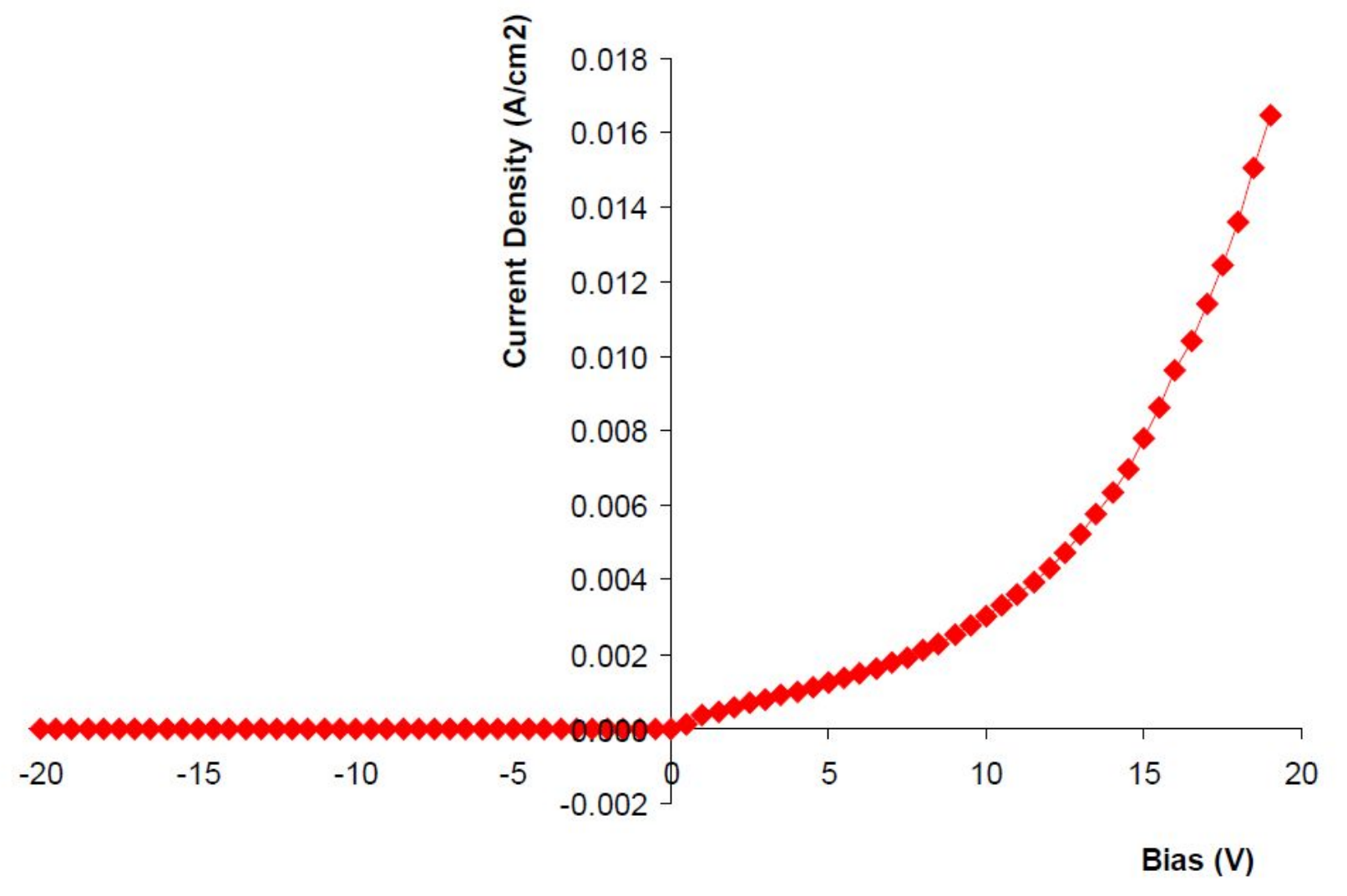

**Figure 5.** IV curve for the NiO/bulk $Ga_2O_3$ heterojunction.

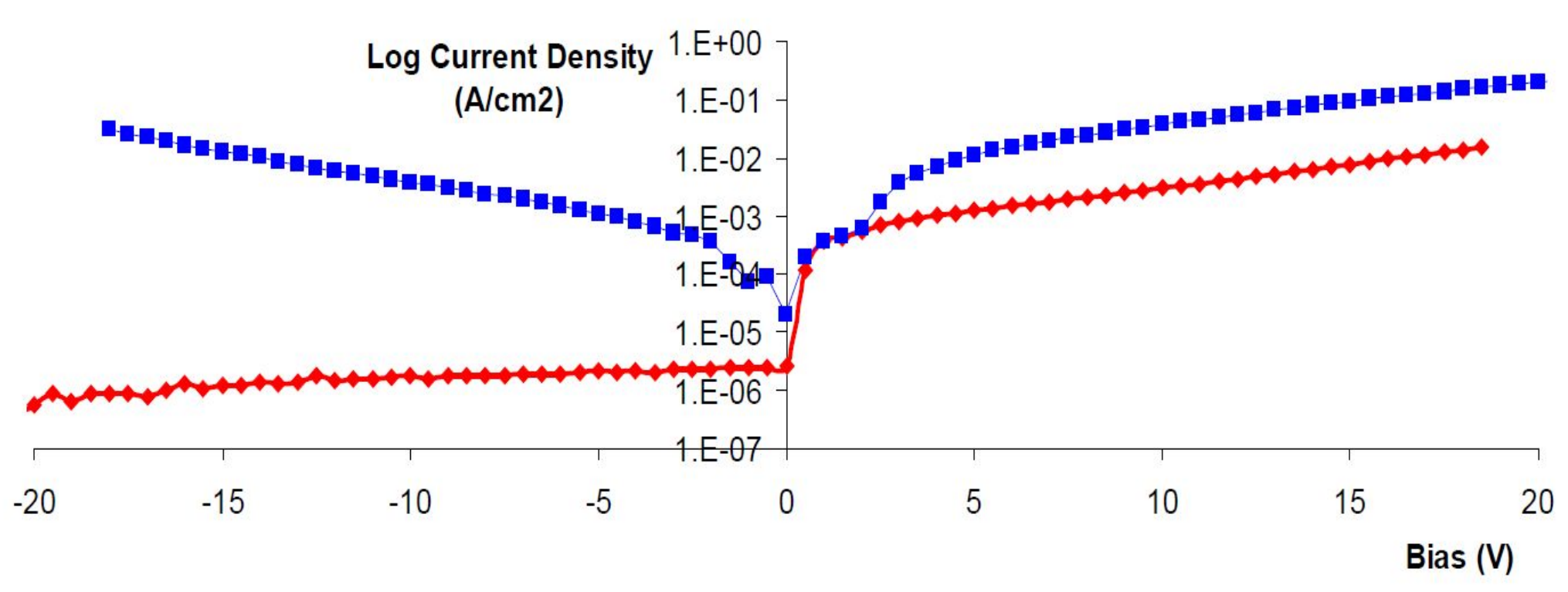

**Figure 6.** IV curves for the NiO/bulk $Ga_2O_3$ heterojunction both with (blue) and without (red) Xenon lamp illumination (current density in log scale).

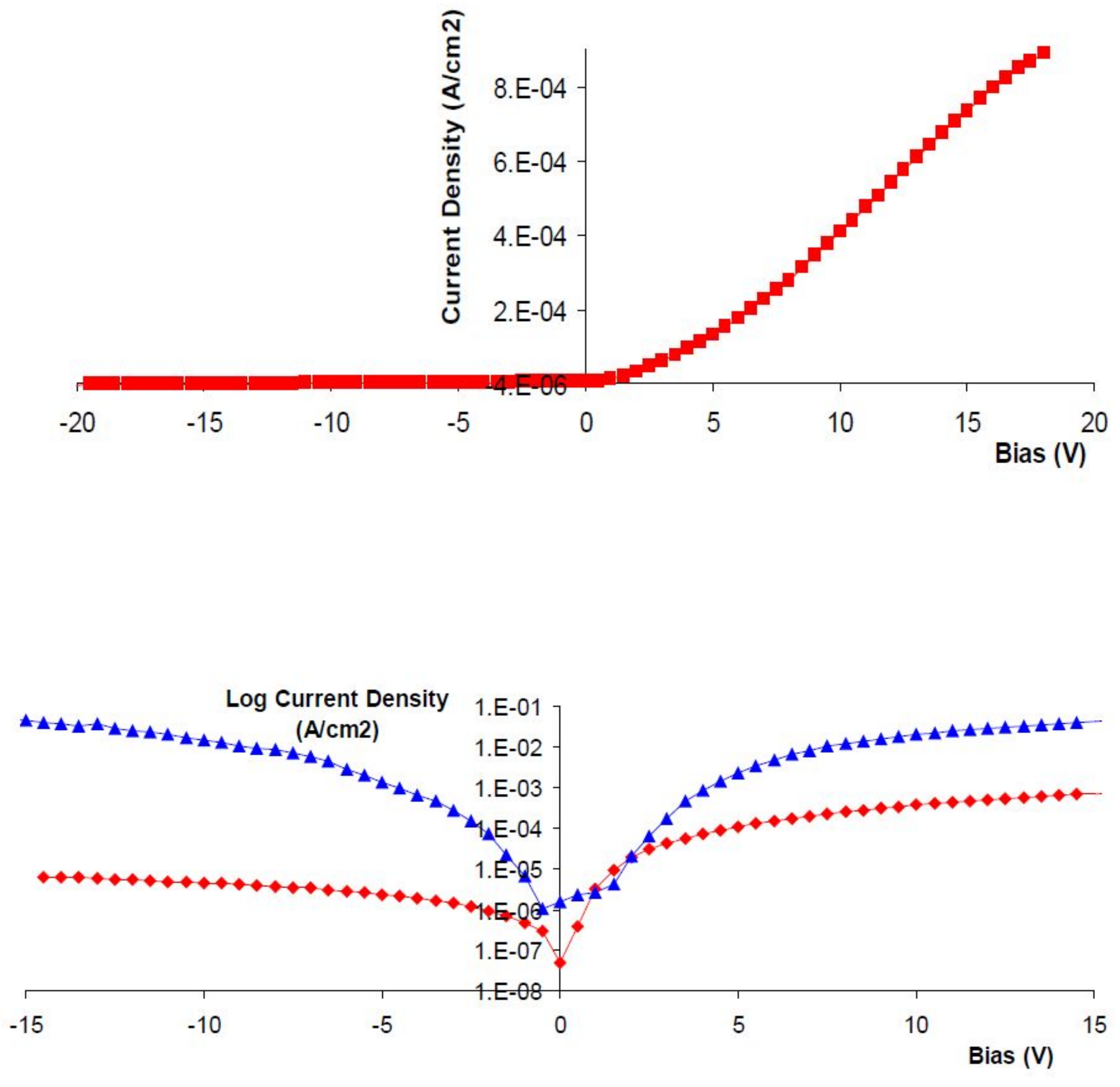

**Figure 10.** I/V curves for the heterojunction without illumination (upper) in linear plot and both with (blue) and without (red) Xenon lamp illumination in log plot (below).

## *IV Characterisation With/Without Illumlnation*

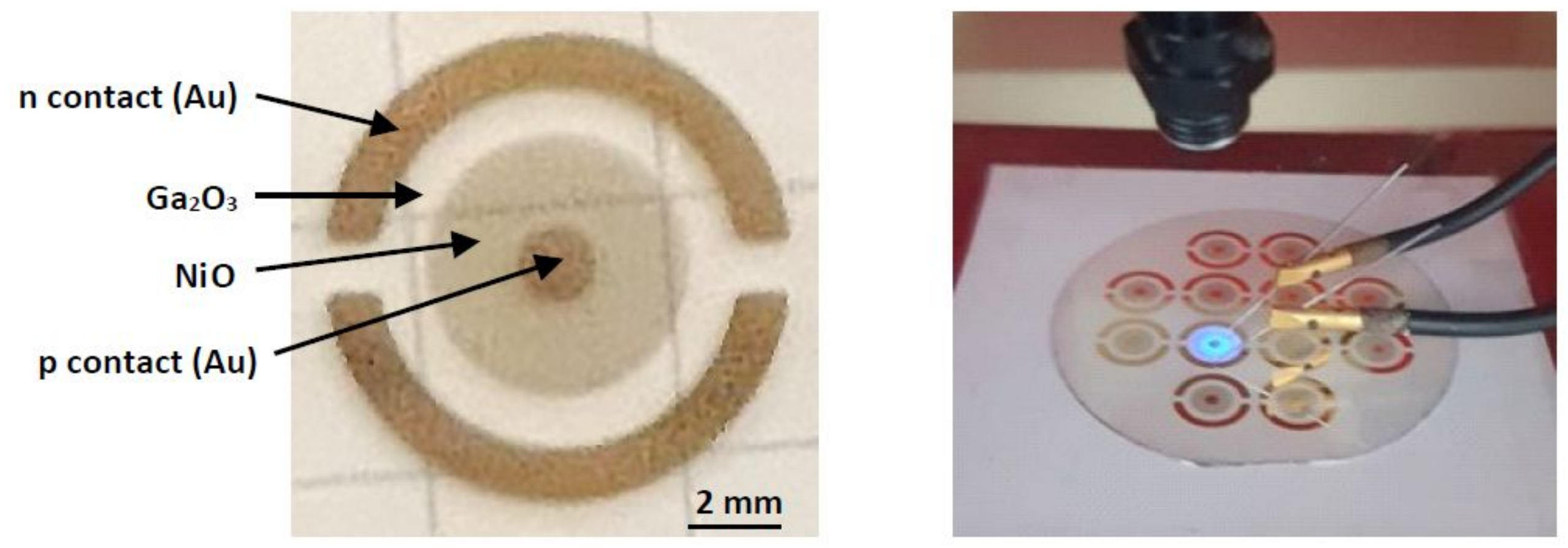

**Figure 3.** Images showing the scale/configuration and IV test set-up (under front illumination via a fiber optic cable) on a probe station for the NiO/$Ga_2O_3$ ring mesa device structures.

## *Time Response of the Devices Upon Shuttering of Xenon Lamp Illumination*

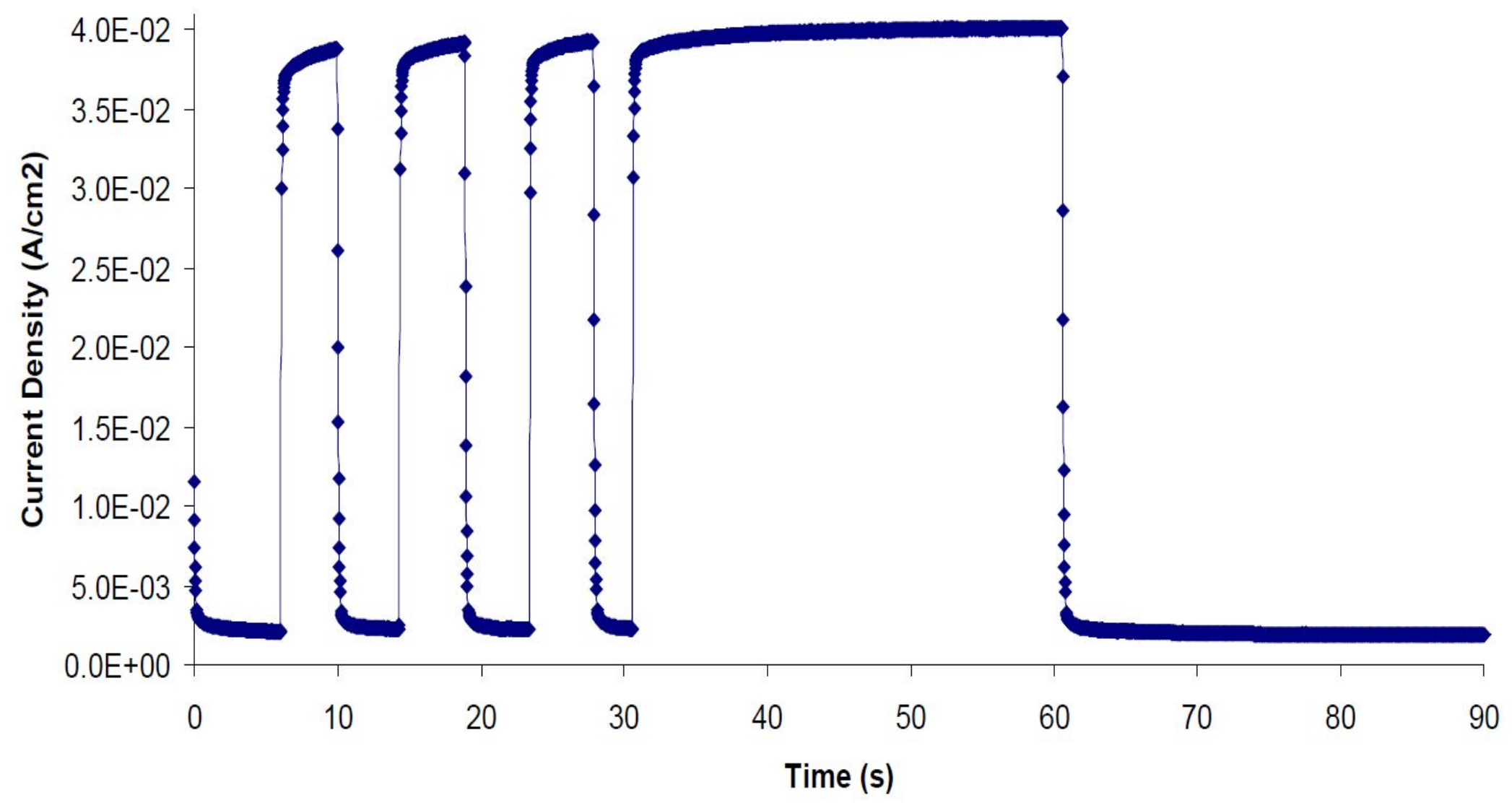

**Figure 7** Device current as a function of time for the p-NiO /bulk n-$Ga_2O_3$ heterojunction under 5V bias with the Xenon lamp illumination being shuttered on and off.

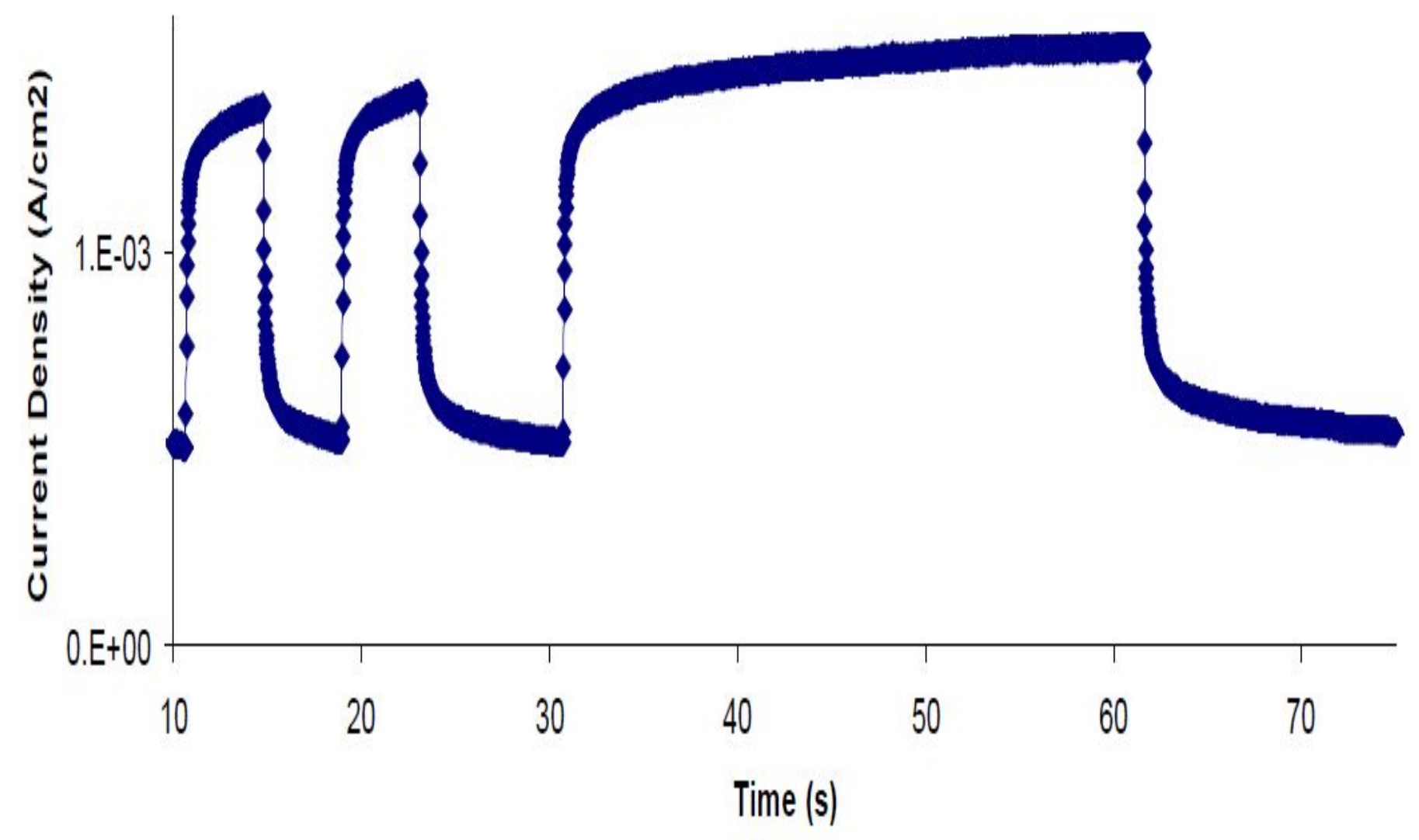

**Figure 12**. Device current as a function of time for the p-NiO/n-$Ga_2O_3$/r-sapphire junction under 1V bias with the Xenon lamp illumination being shuttered on and off.

## *Discussion/Conclusions*

PLD growth was employed to form NiO/Ga2O3 p-n junctions on r-sapphire and commercial bulk Ga2O3 substrates. XRD and optical transmission studies were consistent with the formation of monoclinic β-Ga2O3 and fcc NiO. On the bulk Ga2O3 the NiO showed a preferential (111) orientation while on Ga2O3/r-sapphire the NiO showed a random orientation.

RT optical transmission studies revealed a total transmittance above 80% at wavelengths over 270nm for the Ga2O3 on sapphire and a relatively abrupt absorption edge corresponding to a bandgap of approximately 5.28eV (235nm). The spectrum for the NiO/Ga2O3/r-sapphire showed more absorption over the whole spectrum and an extended NiO absorption edge indicating a bandgap of approximately 3.65eV (340nm).

p n junction devices were formed by depositing gold contacts on the layer stacks using shadow masks in a thermal evaporator. Both heterojunctions showed rectifying IV characteristics. On bulk Ga2O3 the junction showed a forward bias current density over 16mA/cm2 at +20V bias and a reverse bias leakage current over 3 orders of magnitude lower at -20V (1 pA). On Ga2O3/r-sapphire the forward bias current density at +15V was about an order of magnitude lower than for the p-NiO/ bulk n-Ga2O3 heterojunction while the reverse bias leakage current at -15V (~ 20 pA) was an order of magnitude higher. Hence the NiO/bulk Ga2O3 junction was more rectifying.

Upon top illumination of the devices with a Xenon lamp, a distinct increase in current was observed for the IV curves in both devices (four orders of magnitude for -15V reverse bias in the case of the p-NiO/bulk n-Ga2O3 heterojunction). The spectral responsivity for the NiO/Ga2O3/r-sapphire had a FWHM value of 80nm and showed two distinct peaks at about 230nm and 270nm which were taken to be related to photo-generated carriers in the Ga2O3 underlayer. For both devices time response studies showed a 10%/90% rise and fall of the photo-generated current upon shutter open and closing which was relatively abrupt (millisecond range), and there was no evidence of significant persistent photoconductivity.

*Acknowledgements*

AGENCE NATIONALE DE LA RECHERCHE ANR

**CONTACT: sandana@anovation.com**