Threshold Switching in Nickle-Doped Zinc Oxide Based Memristor for Artificial Sensory Applications

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Supplementary information:

Good crystallinity was achieved as the diffracted peaks displayed a good match with the ICDD reference no. 01-089-0510 of ZnO wurtzite hexagonal with a space group of P63mc. As for the NZO (Figure S1a), diffraction peaks of Ni metal were detected at (100), (002), (101), (110), and (202) crystal plane in correlation with standard Ni ICDD Card No. 00-004-0805. This occurrence is attributed to the massive variance in terms of ionic size between Ni^{+} ions and Zn^{2+} ions in the ZnO system. With that being mentioned, the existence of Ni metal seemed to affect the fabrication of ZnO[1]. Based on the XRD pattern, no shifting was observed in the peak position for NZO samples. This indicates that the existence of Ni particles was not slotted into the lattice but squeezed in the grain boundaries of ZnO crystallites[1, 2]. For NZO, as shown in Figure S1(a), it was revealed that the materials have a single phase of ZnO wurtzite hexagonal structure for the Ni content less than 5%. Although the XRD peak position did not exhibit any changes, some alteration was noted for peak intensity and width. In this case, the introduction of Ni did not move the peak to a lower position. In fact, the impurities for peak intensity for Ni metal increased as the stoichiometry increased at peak position (111).

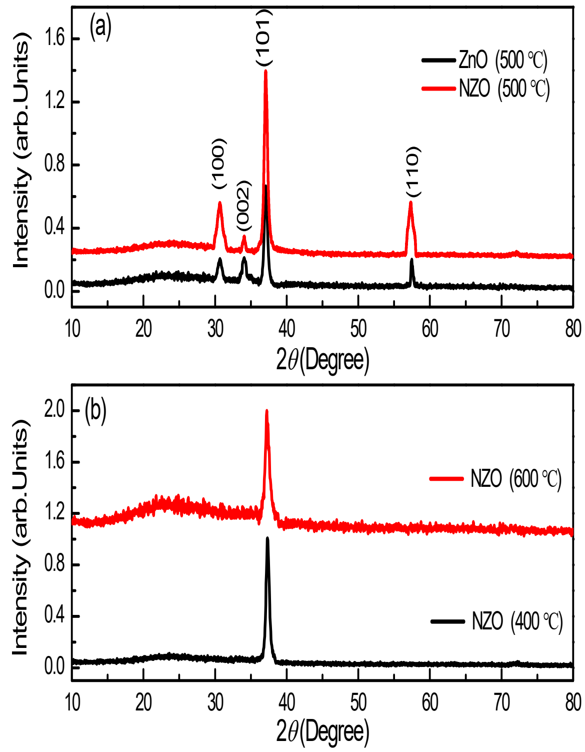


Figure S1(Supporting information). The XRD pattern of both (a) pure ZnO and NZO film. (b) XRD of NZO annealed at 400°C and 600°C.

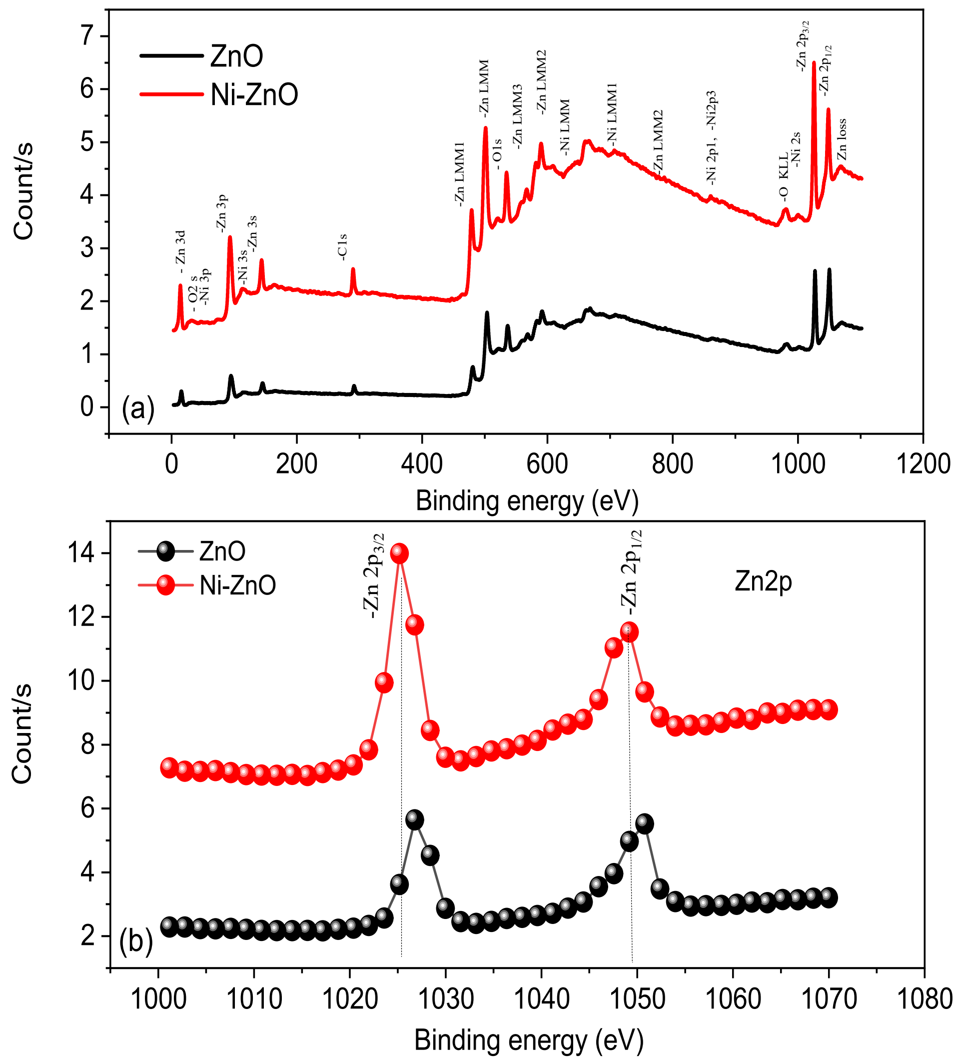
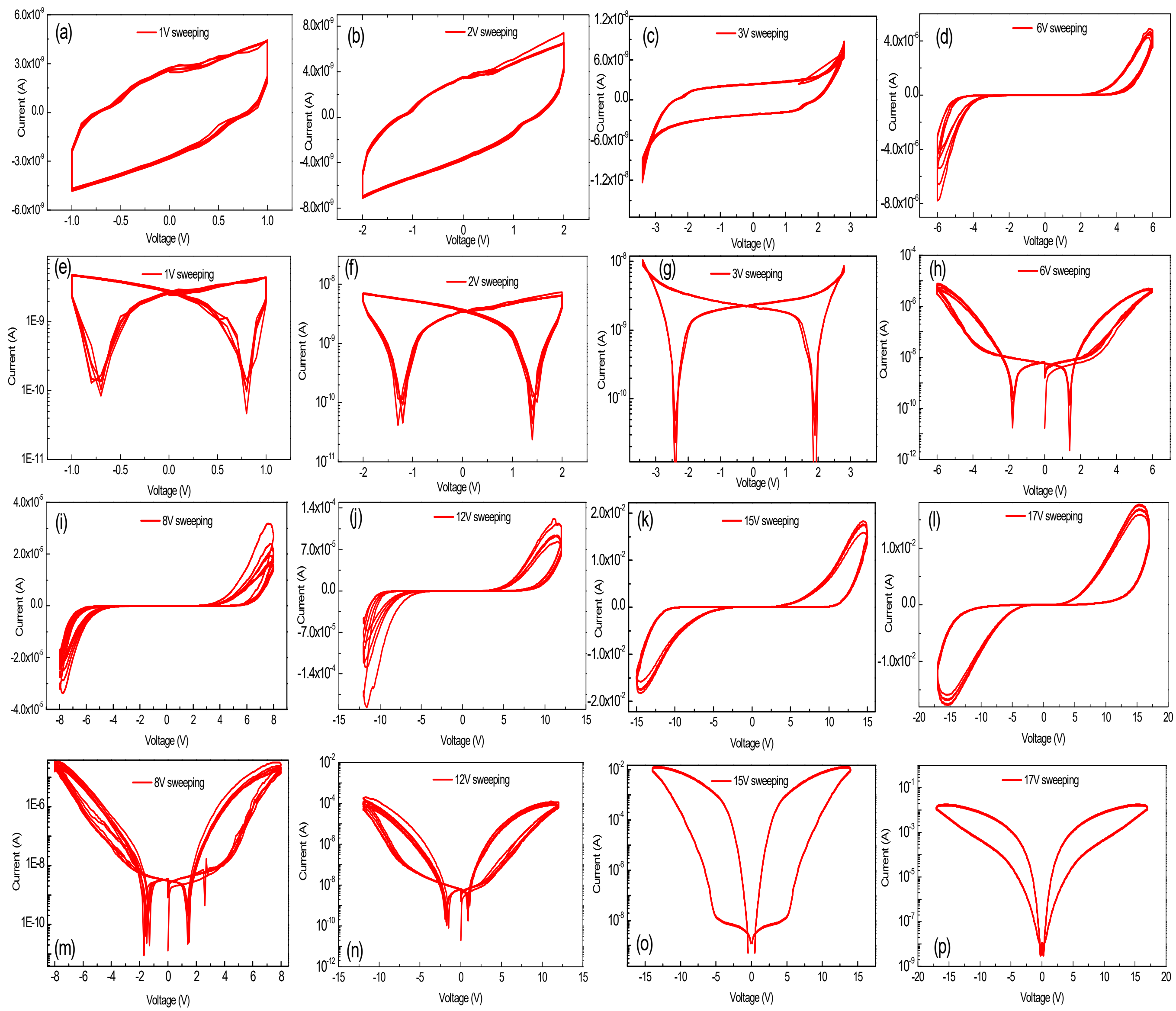


Figure S2(Supporting information). (a) XPS analysis of ZnO and Ni-doped ZnO films (b). Zn 2p of Ni-doped and pure ZnO films.

Supplementary materials:


(a)
1V sweeping
(b)
2V sweeping
(c)
3V sweeping
(d)
6V sweeping
(e)
1V sweeping
(f)
2V sweeping
(g)
3V sweeping
(h)
6V sweeping
(i)
8V sweeping
(j)
12V sweeping
(k)
15V sweeping
(l)
17V sweeping
(m)
8V sweeping
(n)
12V sweeping
(o)
15V sweeping
(p)
17V sweeping
Current (A)
Voltage (V)

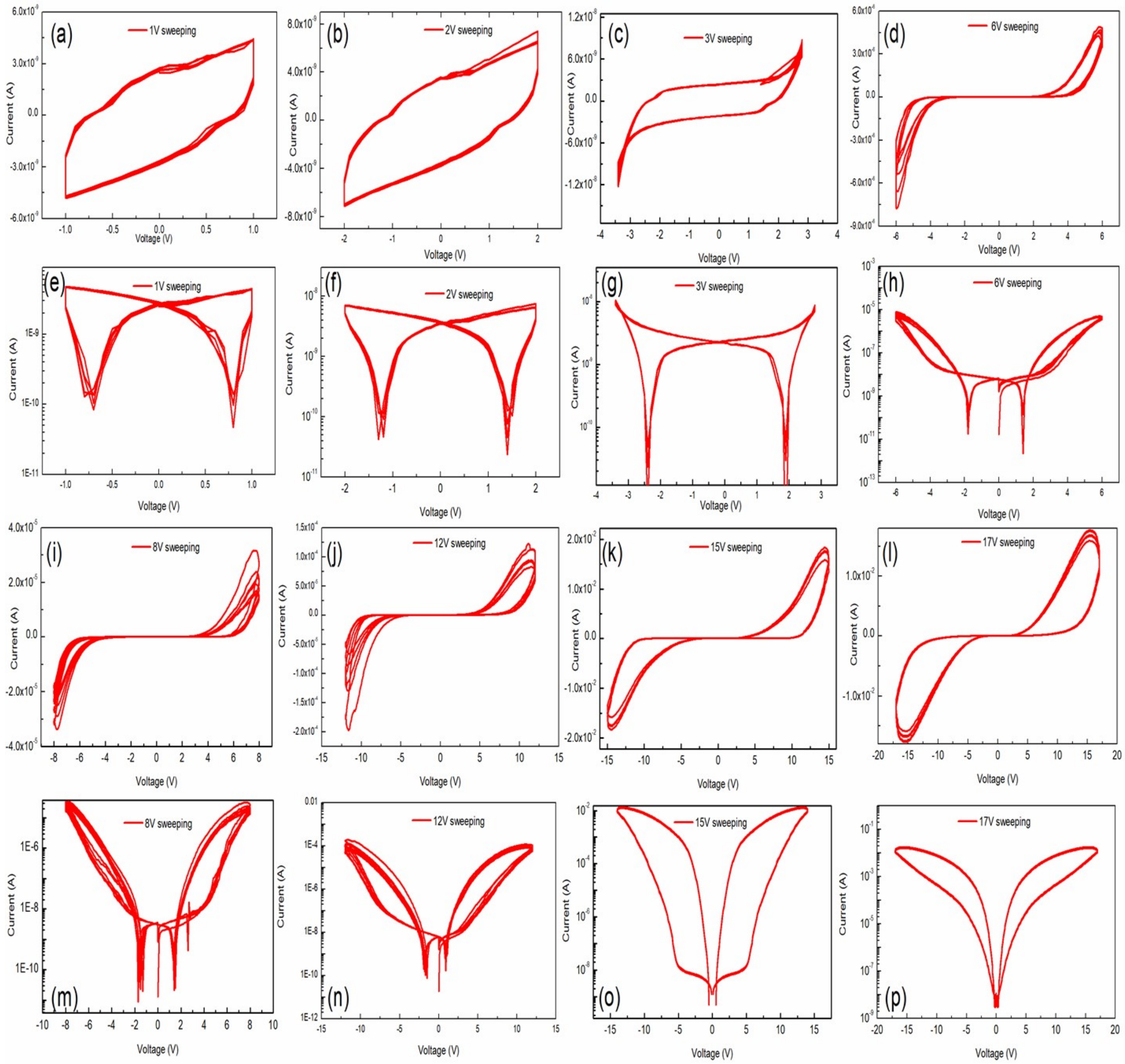


Figure S3 (Supporting information). Sweeping behavior for P^{++}-Si/NZO/Au under sweeping voltages. (a and e) 1 V, (b and f) 2 V, (c and g) 3 V, (d and h) 4V, (i and m) 8 V. (j and n) 10 V, (k and o) 15 V, and (l and p) 17 V in a linear and semi-logarithmic scale.

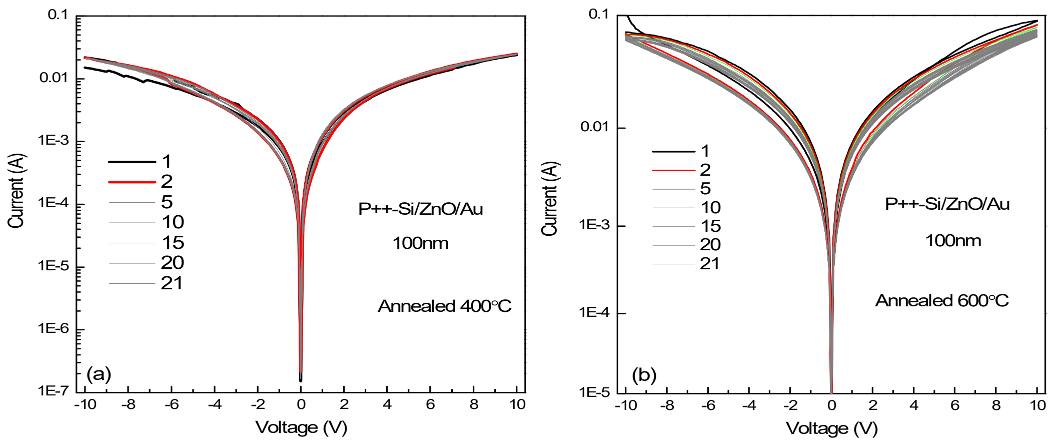


Figure S4 (Supporting information). The I–V sweeping behavior for pure ZnO-based device (a) annealed at 400°C and (b) 600°C.

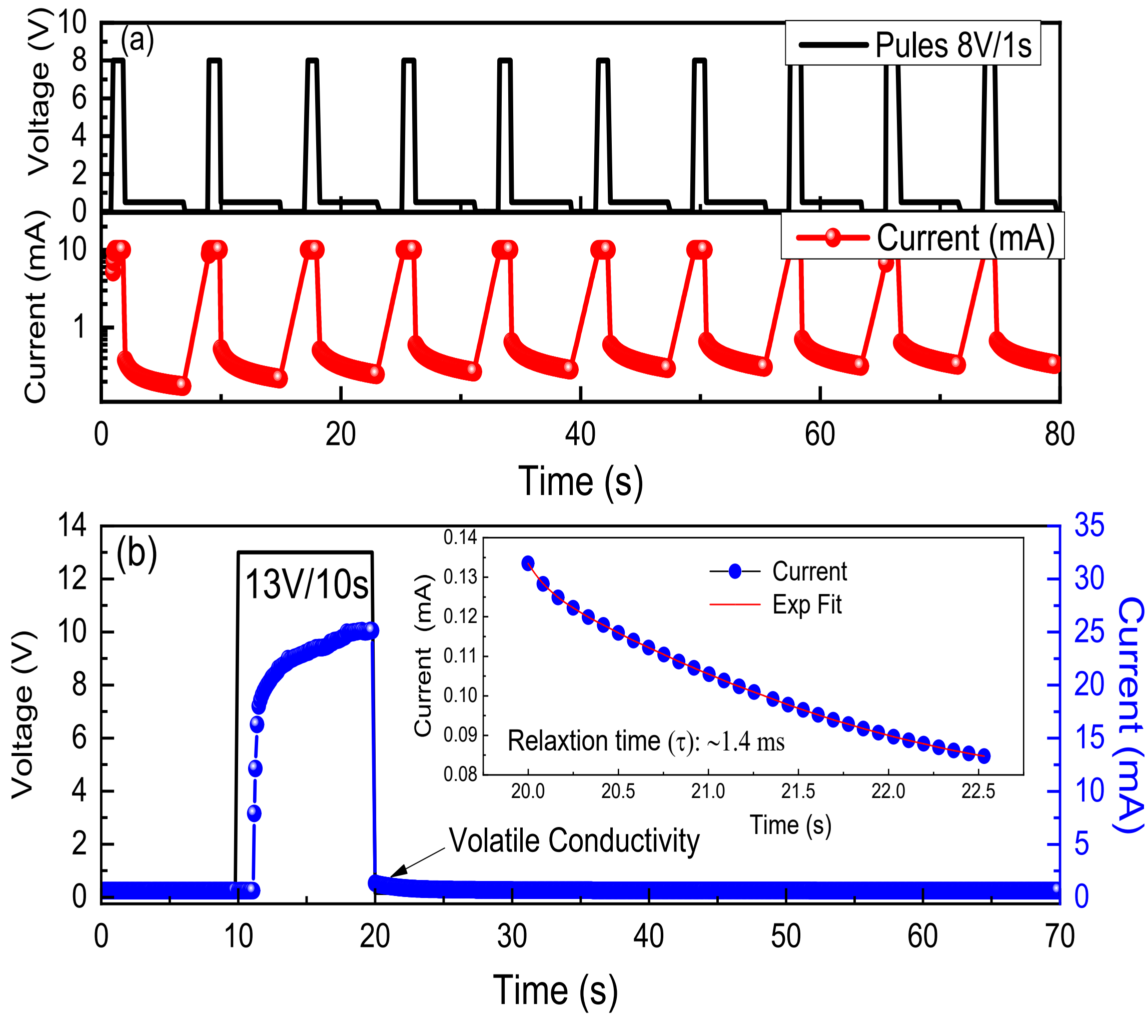


Figure S5 (Supporting information)**.** Relevant plasticity characteristics of P++-Si/NZO/Au system. (a) The repeatable TS with AC pulses. (b) The delay, SET, and relaxation characteristic of electronic synapses, (inset) The relaxation in current level and its exponential decay fitting.

Figure S5(a) displays that ZnO-based devices can be switched between HRS and LRS by SET and RESET pulses. However, in order to form a volatile conductive path, there must be a pulse to maintain the ON state after programming. For Plasticity characterization, first, a short voltage pulse with a pulse width of 10 ms and a pulse height of 0.4 V is applied to the device, and then a long read pulse with a pulse height of 13 V for 10 ms. The short voltage pulse induces threshold switching in the electron nociceptor by switching it from an insulated state to a conducting state. The current abruptly increased to the ON state after a short delay and gradually recovered back to the insulating state, as shown in Figure. S5(b). The relaxation of the electronic synapse is clearly demonstrated in Figure. S5(b). The relaxation time for the given pulse was found to be ~1.4 ms by using the exponential decay function. In order to provide the artificial nociceptor enough time to completely return to the OFF state under zero bias, a long interval (10 ms) is applied between the SET pulse and the read pulse. In order to intentionally apply a small read voltage of 0.4 V in order to extract the real conductance state of the device without affecting its original condition. Since the relaxation interval is large enough (> τ) for spontaneous relaxation, the device exhibits a repeatable threshold switching in continuous pulses. P++-Si/NZO/Au has these dynamic characteristics of repeatable threshold switching using pulses, which is ideal for effectively simulating nociceptors.

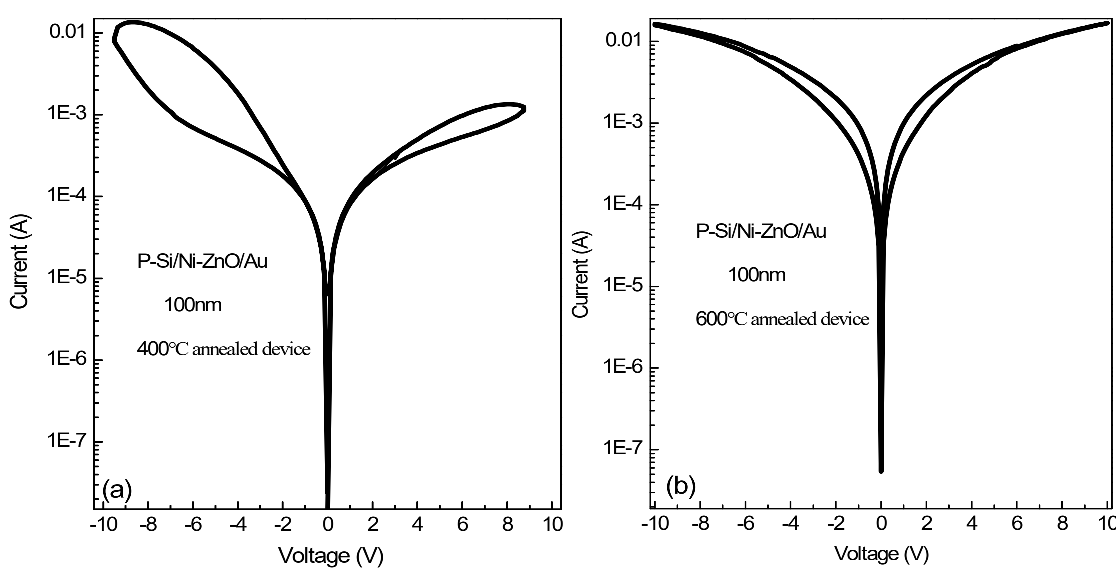


Figure S6 (Supporting information). The I-V characteristic of P++-Si/Ni-ZnO/Au device at different annealing temperature fox example (a) 400°C and (b) 600°C.

[1] Agarwal D, Singh U, Gupta S, Singhal R, Kulriya P, Singh F, et al. Enhanced room temperature ferromagnetism and green photoluminescence in Cu doped ZnO thin film synthesised by neutral beam sputtering. Scientific reports 2019;9:1-12.
[2] Mousavi SM, Mahjoub AR, Abazari R. Facile green fabrication of nanostructural Ni-doped ZnO hollow sphere as an advanced photocatalytic material for dye degradation. Journal of Molecular Liquids 2017;242:512-9.