Response to "Comment on 'p-type behavior from Sb-doped ZnO heterojunction diodes'" [Appl. Phys. Lett. 88, 112108 (2006)]

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In the comment,[1] Lin *et al.* believe that the results in our paper[2] are different from those in the textbook.[3] They conclude that our explanation of the device operation mechanism is wrong. However, we believe that the device mechanism and interpretation given by us are reasonable.

The device structure we have is a Sb-doped *p*-type ZnO/*n*-type Si with Ohmic contacts on the top ZnO and bottom Si layer. The band alignment is shown in the inset of Fig. 2 of Ref. 2. A quantum well for holes is formed in the *n*-type Si side. Hence, the narrow band-gap Si is inverted in the interface when connecting to *p*-ZnO. During the forward operation of our diode (positive bias on *n*-type Si), holes will overcome a "Schottky barrier" (effective band offset in the valence band edge or the Fermi level in the inverted Si quantum well to the valence band edge of ZnO in the interface). In other words, holes are from Si to ZnO, rather than in the opposite direction in this forward operation. This voltage polarity (positive on *n*-type Si) results in the rectifying characteristics. There is not much electron transport in this bias condition making it a "*p*-type diode" with unipolar hole transport rather than bipolar transport in a regular diode, therefore, we say it "behaves" like a *p*-type Schottky diode. Textbook also suggests that the Schottky behavior can be obtained by replacing the metal with a narrower band-gap semiconductor.

Lin *et al.* argue about the depletion width of an idealized diode to interpret *I-V* and low bias *C-V* characteristics obtained for our diode. This argument is not the case here due to the accumulation of holes in the quantum well in the interface. During the reverse operation of our diode (positive on *p*-type ZnO), we found that the current is similar to the reverse saturated current of a normal diode. In fact, it is evident in Fig. 2 of Ref. 2 that the amplitude of the current increases as the reverse bias increases. This is a typical characteristic of nonidealized leakage current such as recombination current. The reason of forming this recombination leakage current in our diode is that this voltage polarity has to first convert the inverted Si (the interface) to the depletion, and then to normal when the injected electrons from *n*-Si recombines with holes in the quantum well before the holes from *p*-type ZnO have available states to move on. Therefore, this bias condition results in limited current mainly due to the recombination current.

Moreover, the double Schottky behavior refers to back-to-back-Schottky (or metal-semiconductor-metal) behavior, i.e., showing saturation in both the regions of biasing as one of them is always reverse biased for either polarity. Lin *et al.* compared the curve with those shown in the textbook and

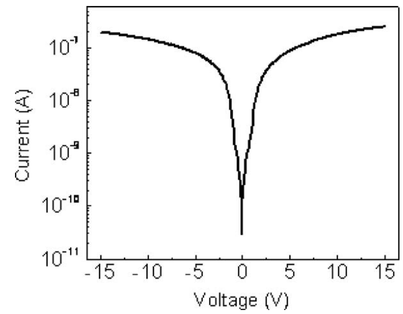

FIG. 1. *I-V* characteristics of two as-deposited contacts on a semilogarithmic scale. The absolute value of current is used.

believe, for example, that the curve in the inset of Fig. 1(a) of our paper[2] is wrong. As a matter of fact, Lin *et al.* did not read the figure carefully. In the inset, the *y* axis is linear. Here, we have replotted the characteristics shown in the inset of Fig. 1(a) in this response on a semi-logarithmic scale in Fig. 1. This appearance should now look like typical characteristic of back-to-back Schottky device in a textbook. Similarly, there is also nothing wrong in our *C-V* characteristics.

In summary, due to the unipolar hole transport and Schottky diode characteristics, we stated that our diode behaves like a *p*-type Schottky diode, which is reasonable. Lin *et al.* compared our diode characteristics with that of an idealized diode from textbook and did not think that it is appropriate to use *p*-type Schottky diode for our device as this terminology has been utilized for metal/*p*-semiconductor structure already. We, however, would not argue with this; as a matter of fact, the device is a heterojunction diode clearly stated in the title of the paper anyway. The comment of Lin *et al.* starts with a statement that our explanation in our paper is wrong, because they believe the results are different from the curves from the textbook, and then suggested we have to further investigate the diode operation mechanism. Although the terminology may have confused Lin *et al.*, the format of the comment, namely, "this is wrong" and "the authors should do further investigation" has no scientific content and cannot add any new knowledge to the existing science and engineering field.

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