AIP | Applied Physics Letters

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Citation: Appl. Phys. Lett. **102**, 246101 (2013); doi: 10.1063/1.4811549
View online: http://dx.doi.org/10.1063/1.4811549
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v102/i24
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Comment on "Origin of breakdown mechanism in multicrystalline silicon solar cells" [Appl. Phys. Lett. 101, 093903 (2012)]

Jan-Martin Wagner,[1] Jan Bauer,[2] and Otwin Breitenstein[2]
[1]*Institute for General Materials Science, Faculty of Engineering, Christian Albrechts University of Kiel, Kaiserstr. 2, 24143 Kiel, Germany*
[2]*Max Planck Institute of Microstructure Physics, Weinberg 2, 06120 Halle, Germany*

(Received 17 December 2012; accepted 29 May 2013; published online 17 June 2013)

[http://dx.doi.org/10.1063/1.4811549]

In their recent publication,[1] Zhang *et al.* investigate the temperature variation of forward and reverse *J–V* characteristics of a small piece (10×12 mm^2; denoted as "S_{II}") cut from a multicrystalline silicon solar cell made from a boron-doped wafer by diffusing-in a phosphorous-doped emitter. For not-too-large reverse bias voltages (where usually defect-induced type-2 breakdown dominates[2]), they find a positive temperature coefficient of the reverse current, from which they conclude that Zener breakdown is the major breakdown mechanism.

However, this conclusion is highly questionable since the investigated temperature coefficient does not refer to the local breakdown currents but to the total current. As we have shown earlier,[3] at least for not-too-high temperatures, the local breakdown currents may have a negative temperature coefficient even though the global current has a positive one for such low reverse voltages. The reason for this seeming discrepancy is that in multicrystalline silicon solar cells, the reverse current does not only flow at localized breakdown sites but is also found throughout the area of the solar cell, there having a positive temperature coefficient.[3]

Obviously, Zhang *et al.* assume that their cut-out sample "S_{II}" consists only of breakdown areas or is at least dominated by them. However, this cannot be true since type-2 breakdown sites are of highly localized, micron-sized nature as shown by Wagner *et al.*,[3] Lausch *et al.*,[4] Kwapil *et al.*,[5] Schneemann *et al.*,[6] Gundel *et al.*,[7] and Breitenstein *et al.*[2] The temperature-dependent reverse-bias *I–V* characteristics presented by Zhang *et al.* for their sample S_{II} are qualitatively indistinguishable from those of a complete cell (as presented, e.g., in Ref. 3), showing a soft-exponential behavior. However, single breakdown sites are expected to show a more or less linear characteristic, as can be inferred from Ref. 6.

In the remainder of their publication,[1] without any justification, the authors discuss the forward-bias current of their crystalline Si bulk p–n junction solar cell in terms of the behavior of an amorphous/crystalline heterojunction (Refs. 14 and 17–19), which is wrong, since a silicon solar cell is not a heterojunction but a homojunction device. Moreover, they explicitly mention an enhanced Zener tunneling effect for high forward voltage. However, in a homojunction (as investigated in Ref. 1), the junction current for forward voltage is a diffusion current which can be very well described by the Shockley diode equation;[8,9] there is no tunneling involved at all. Therefore, their Fig. 4 is obsolete since it refers to a model [Eq. (3)] which is not applicable here.

The forward *I–V* characteristics in Fig. 3 of Zhang *et al.*[1] do not show any special behavior, except that they are measured up to very high current densities, where the characteristics are more influenced by the series resistance of the measurement circuit than by the diode properties. Obviously, the voltage on the *x*-axis of Fig. 3 is not the voltage across the cell but that displayed at the power supply. It can be expected that also a sample with a lower amount of type-2 breakdown sites will show the same temperature behavior. The conclusions based on the characteristics shown in Fig. 3 suffer from the same mistake as those derived from Fig. 2: As global measurements, these characteristics do not represent the behavior of the local breakdown sites but that of the sample S_{II} as a whole. Hence the idea of Zhang *et al.* that the temperature dependence of the forward characteristic might give a clue about the state of the p–n junction at breakdown sites and/or the type of breakdown involved is not applicable to their measurements.

For reverse bias, Zener tunneling is expected in silicon junctions at a field strength of 10^6 V/cm, which is only achievable with base doping concentrations higher than 5×10^{17} cm^{-3} and the breakdown voltage is then about -5 V.[9,10] Neither the high base doping concentration can be expected in the samples used by Zhang *et al.* nor breakdown voltages of about -5 V are shown by Zhang *et al.* Instead the reverse *J–V* characteristics in Fig. 2 show typical breakdown voltages of about -11 V.[1]

Summing up, we find that on the basis of the measurements published by Zhang *et al.*,[1] the conclusions they draw are highly questionable, containing basic misconceptions regarding the microscopic nature of type-2 breakdown.

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