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Letter

Localized irradiation effects on tunnel diode transitions in multi-junction concentrator solar cells

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ABSTRACT

Multi-junction concentrator solar cells incorporate tunnel diodes that undergo a transition from high-conductance tunneling to low-conductance thermal diffusion behavior, typically at threshold current densities of the order of 10^2–10^3 mA/mm^2. We present experimental evidence of a prominent heretofore unrecognized dependence of threshold current density on the degree of localized irradiation, in different solar cell architectures. We also show that solar cells with non-uniform metallization can exhibit an additional spatial dependence to the tunnel diode threshold current density. These previously undiscovered phenomena – which should be observable in all non-uniformly irradiated photovoltaic tunnel diodes – are interpreted as being derived from the lateral spreading of excess majority carriers (analogous to current spreading in light-emitting diodes (LEDs)). The consequences for concentrator photovoltaics are addressed.

An integral part of ultra-efficient multi-junction solar cells is the tunnel diode, consisting of highly doped, optically transparent layers only a few nm thick and forming a tunnel junction between the valence and the conduction bands. These junctions electrically connect the individual sub-cells of monolithic multi-junction solar cells. A tunnel diode's signature curve of current density J as a function of voltage V is characterized by a peak J_p beyond which the diode enters an unstable region of negative differential electrical resistance, undergoing a transition from low-resistance tunneling to high-resistance thermal diffusion behavior that markedly worsens solar cell efficiency [1–10]. Manufacturers tailor concentrator cells so that J_p is not exceeded by the maximum anticipated short circuit current densities J_{sc} that often correspond to solar irradiance levels of thousands of suns (1 sun = 1 mW/mm^2).

The tunnel diode transition (TDT) has been construed as a characteristic of the entire cell, effectively independent of flux distribution—germane because solar concentrator optics often produce strongly inhomogeneous flux maps [11,12]. In this paper, we demonstrate heretofore unrecognized, unexplored and nominally universal TDT characteristics: under highly concentrated and strongly localized sunlight, the current density of the TDT can vary significantly with the degree of localized irradiation. These fundamental trends also impact the design and the operation of large-scale concentrator photovoltaic systems (*vide infra*).

High-irradiance experiments (up to 10,000 suns) were performed with a fiber-optic mini-dish concentrator detailed previously [4,13,14]. Solar-beam radiation was concentrated outdoors and delivered indoors onto the solar cell being tested via a high-transmissivity optical fiber of varying quartz-core diameters d_f and numerical apertures NA based on commercial availability: (1) $d_f = 2.00$ mm, $NA = 0.40$, (2) $d_f = 1.00$ mm, $NA = 0.66$, (3) $d_f = 0.60$ mm, $NA = 0.48$ and (4) $d_f = 0.20$ mm, $NA = 0.66$. Fiber proximity to the cell ensured that light spillage beyond an area equal to that of the fiber tip did not exceed 1%. Current–voltage (I–V) curves were traced from short circuit to open circuit with a picoscope of accuracy 0.3%, during periods with solar spectra close to AM1.5 [13]. Each cell's I_{sc} was found to be proportional to the solar radiation on the cell. Cell temperature was maintained at 25 ± 1 °C via thermal bonding to a thermoelectric controller. The dark I–V curves of specially prepared isolated tunnel diode structures of different areas were measured via a sweep from low to high voltage and backward with a Kepco bipolar voltage source and a 4-wire contact [2], the current being measured with a high-precision 10 mΩ resistor.

The variation of the TDT with the extent of localized irradiation was first detected during experiments on a 3-junction

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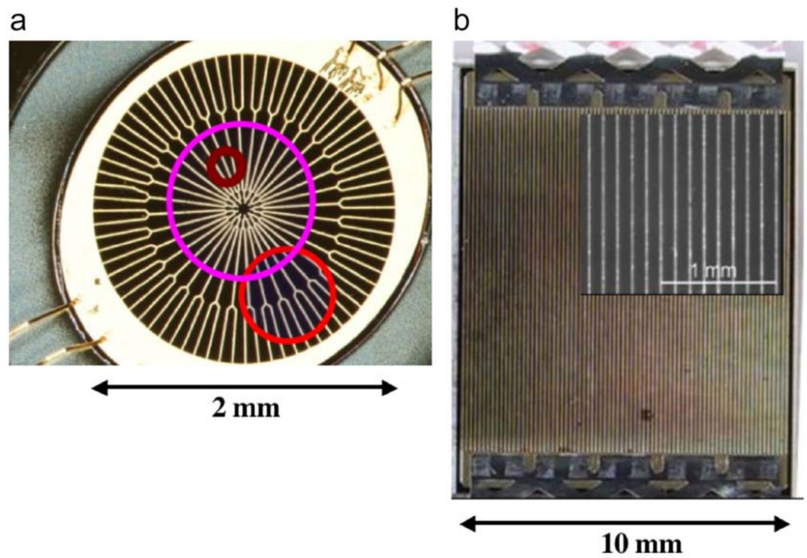

Fig. 1. (a) Circular 2.00-mm-diameter (active area) cells with non-uniform metallization. Superimposed circles indicate sample positions for the optical fibers with 1.00, 0.60 and 0.20 mm diameter. The cell's full active area was uniformly illuminated with the 2.00 mm fiber. (b) Square 100 mm^2 (active area) 3-junction cell [14]. The inset magnifies the uniform parallel-strip metallization. (Cell manufacturers invariably treat tunnel diode details as proprietary. Hence tunnel diode layer particulars were unavailable to us. Nonetheless, because the nature of the key phenomena identified here should be universal for all tunnel diodes, the precise structure of the tunnel diode layers is inessential. The emphasis is not on differences among assorted tunnel diodes, but on the fact that three distinct types of solar cells exhibit the same prominent TDT trends.)

GaInP/GaInAs/Ge cell with an active area of 3.14 mm^2 and non-uniform metallization densest at the center (Fig. 1a). Experiments were then conducted on a single-junction GaInP cell with an underlying tunnel diode produced expressly for tunnel diode assessment; this cell has the same active area and metallization pattern as that of the 3-junction cell.

These results prompted revisiting an earlier experimental investigation [4] of the TDT in a square 100 mm^2 3-junction GaInP/GaAs/Ge cell of uniform metallization (Fig. 1b) where these special aspects of the TDT were not probed. If the particular localized irradiation TDT dependence noted here is universal, then it must appear in this cell when a suitably modified irradiation strategy is applied.

To check whether the TDT is independent of tunnel diode area, we first measured the dark *I–V* curves of isolated n-GaInP/p-GaAs tunnel diode structures similar to those of the single-junction GaInP cell. These diodes were mesa etched to circular pillars with diameters of 1.4, 2.2 and 2.9 mm and covered with metal. The measurements confirmed that J_p is independent of the diode area to within our measured standard deviation of $\pm$8%.

Next, in order to probe the dependence of the TDT on the size of the illuminated area, we measured solar cell *I–V* curves, traced from short circuit to open circuit, as a function of irradiance with optical fibers of varying sizes centered on the cell. Representative results for the 3-junction 3.14 mm^2 cell with the 1.00 mm fiber are illustrated in Fig. 2, where a high fill factor is exhibited up to a localized irradiance of 838 suns, a threshold above which the onset of the TDT is apparent in the dip in the *I–V* curve, with this dip growing more pronounced as irradiance increases.

The tunnel diode peak current I_p is best ascertained by increasing irradiation and tracking the *I–V* curve from short circuit to open circuit, until the characteristic dip in the *I–V* curve appears [2]. Accordingly, with I_p taken as the highest I_{sc} measured without observing a TDT, J_p was calculated as the ratio of I_p to the illuminated (optical fiber) area. Fig. 3 summarizes J_p values measured at the center of both of the 3.14 mm^2 cells and across the surface of the 100 mm^2 cell.

A prominent increase in J_p at sufficiently small optical fiber area is evident. The TDTs measured with the 0.60, 1.00 and

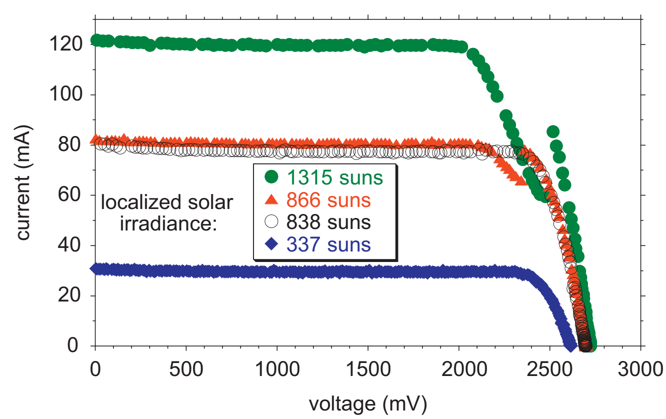

Fig. 2. *I–V* curves of the 3-junction 3.14 mm^2 cell at varying localized solar irradiance performed with the 1.00 mm optical fiber centered on the cell.

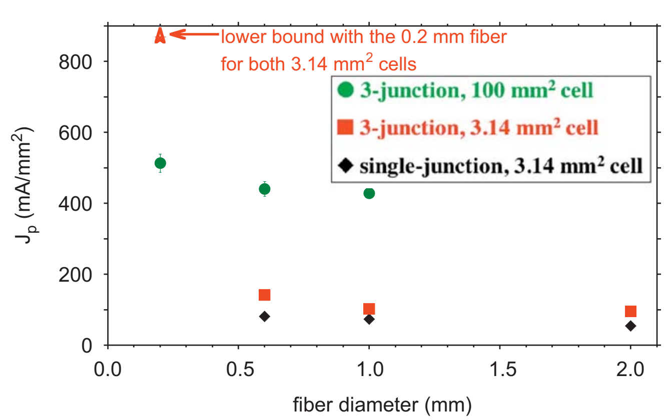

Fig. 3. TDT J_p values measured at the center of both of the 3.14 mm^2 cells and across the surface of the 100 mm^2 cell. The standard deviations for the latter are consistent with the manufacturer's report [15] of inherent variations in tunnel diode quality over areas of 100 mm^2.