Optimization of Cells for Microscale Themophotovoltaic Energy Conversion

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In 2000 we succeeded in our effort to provide the first experimental demonstration that a significant increase in ThermoPhotoVoltaic (TPV) energy conversion (5 to 10 times) is obtained by positioning the active diode surface in extreme close proximity to the radiator (on the order of a tenth of the wavelength of the radiation, or less). The demonstration of this proximity effect is the first step in the creation of a new class of Microscale ThermoPhotoVoltaic (MTPV) devices which promise to make the extraction of electrical energy from a wide variety of heat sources practical and to provide a new class of compact, portable sources of electricity. Moreover, MTPVs will be able to utilize thermal energy now discarded as waste heat, and will enable increases in the overall efficiency of many complex systems.

In the past year we have continued to fabricate TPV cells, but have concentrated on modeling and understanding how best to optimize the basic TPV device structure. This work includes studying electrical, optical, and thermal effects in the devices. The goal was to identify loss mechanisms in the devices and to modify the heterostructure and device designs to increase the internal device efficiency. The material being used for the MTPV system is InAs, with a bandgap of 0.385 eV at 300 K. InAs is highly susceptible to Auger recombination, the dominant recombination process when the dopant concentration is more than two orders of magnitude above the intrinsic concentration of carriers (ni=1.3 x1015 cm-3). Thus, the dopant concentration must be low to prevent recombination of the photogenerated carriers and maximizing the current efficiency of the photovoltaic. This impacts the device as follows: 1) the saturation current density is high, and 2) the open circuit voltage is low (the maximum value of the open circuit voltage is the built-in potential of the junction. These effects adversely affect the power efficiency and the fill factor.

A solution to this problem was to create a short device to minimize series resistance and recombination, lightly doped, and encapsulated with larger bandgap material. The larger bandgap material prevents the photogenerated carriers from recombining at the ohmic contacts and reflects them into the junction. Also, a backside reflector would serve as a means to further increase the efficiency. An example structure is shown in the Figure 4 below. The simulated current efficiency of this structure, (Imax power/Iphoton flux) is 60% at 1 watt/cm2 with the energy of the photon matched at the band gap, and a power efficiency of 10% with the same conditions. Previous devices that were simulated had typically 40% current efficiencies and 3% power efficiencies.

Another aspect of our modeling effort has been directed at understanding the impact of the proximity effect on overall system efficiency. To the first order one would expect that while the output level of a cell increases due to the proximity effect, the cell efficiency remains the same. Closer consideration, however, reveals that while the efficiency of the cell in converting absorbed photons to junction current will not increase, the overall power conversion efficiency will increase because of the concentrator effect. That is to say, because the diode characteristic is exponential, and the output power depends on the maximum of the product of the cell current and cell voltage, the power conversion efficiency of a TPV cell increases as one drives it harder, i.e., with more intense illumination and therefore larger short circuit current.

The parameter that matters in this situation is the ratio of the short circuit photocurrent to the reverse saturation current of the diode. The larger this ratio, the better, particularly when the ratio is relatively low. That is to say, if the ratio is already very high, as it is in the case of a silicon solar cell illuminated by sun light, for example, then increasing it by a factor of 10 improves the power conversion efficiency only a few percent, and it must increase by several orders of magnitude to have an appreciable effect. When this ratio is low (101 to 104, for example), however, as it is in the present case because we have narrow bandgap diodes (i.e. large saturation current) and weak illumination (i.e. small photocurrent), then increasing the ratio by even a factor of 10 can have a meaningful effect and can increase the efficiency 15 to 20%. Thus the proximity effect has a dual impact on TPV cells. It significantly increases their rate of thermal-to-electrical energy conversion, and it increases the efficiency of this conversion.