

## Enhanced photogeneration of carriers in a semiconductor via coupling across a nonisothermal nanoscale vacuum gap

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Enhanced generation of carriers when a thermophotovoltaic cell is placed in submicron proximity to a heated surface is demonstrated using custom-designed InAs photodiodes and special silicon-based heater chips produced using microelectromechanical system techniques. The short-circuit current of the photocells is shown to increase sharply (up to fivefold) when the spacing between the heater and photodiode surfaces is reduced, while at the same time, the heater temperature decreases, consistent with increased radiative transfer between the two surfaces. By varying the spacing sinusoidally (at up to 1 kHz), it is demonstrated that the increase in the short-circuit current occurs in phase with the decrease in separation, thereby ruling out thermal effects. It is argued that the increase in short-circuit current is due to increased evanescent coupling of blackbody radiation from the hot surface to the cold photocell, consistent with recent theoretical predictions. The demonstration of this effect is the initial step in the development of a class of energy conversion devices. © 2001 American Institute of Physics. [DOI: 10.1063/1.1400762]

It has been proposed that the electromagnetic energy transfer in a thermophotovoltaic (TPV) system can be increased by placing the emitter in close proximity to the photovoltaic receiver.<sup>1</sup> The increased flux should manifest itself as an increase in the electrical output of the photovoltaic cell. This letter reports on the experimental demonstration of this effect.

Planck's Law gives the radiant exchange between two infinite parallel surfaces at different temperatures. Planck indicated that his law applies only if the dimensions of the system are large compared to the wavelengths of the radiation.<sup>2</sup> It has been predicted theoretically and shown experimentally that the radiant heat transfer between two opposing surfaces at different temperatures, separated by a vacuum gap, can be increased significantly by decreasing the spacing between the two surfaces to a fraction of the wavelengths of the radiant energy.<sup>3-9</sup> In parallel with this work, TPV has been developed wherein a heated surface (the emitter) radiates photons to a low-band-gap photovoltaic cell that converts them to electric power.<sup>10-13</sup> The use of this small-gap coupling to increase the TPV output has been proposed and studied theoretically.<sup>1,14-17</sup> Experimental demonstration of this effect was done by placing a hot Si chip on a cooled InAs photovoltaic chip separated by SiO<sub>2</sub> spacers, which maintained the physical gap between the two surfaces, as shown in Fig. 1.

A 500- $\mu\text{m}$ -thick "heater chip," shown schematically in Fig. 1, was devised to provide the following functions: submicron gaps between it and the photovoltaic cell, a capacitor plate to allow measurement of the gap, and a controlled hot surface. The silicon heater chip was fabricated by microelec-

tronic system techniques to leave a series of 6- $\mu\text{m}$ -diam oxide mesas on the front, which acted as spacers to determine the separation of the heater and photovoltaic cell. Figure 2 shows two 1- $\mu\text{m}$ -high SiO<sub>2</sub> spacers similar to those used. The back of the chips was coated with a chemical-vapor-deposition oxide insulator and patterned to give a contact window. The backs were also metallized with a thin film of titanium and platinum (100 nm/200 nm). The film was patterned to provide a contact to the bulk of the chip, which acted as the capacitor plate; a 180  $\Omega$  resistor, which was used for temperature measurement; and a 10  $\Omega$  resistor used as a heater. The perimeter of the chip was plasma etched down about 15  $\mu\text{m}$  in the scribe streets so that any burrs that might occur during wafer sawing would not interfere with the gap spacing. The heater chip is 2.2 $\times$ 2.2 mm in size.

Custom TPV cells were designed and fabricated from InAs epitaxial layer structures grown by solid-source molecular-beam epitaxy on *p*-type InAs substrates. The growth was done using *in situ* oxide desorption and a two-step, two-temperature growth sequence optimized to achieve two-dimensional growth and give a very smooth final surface.

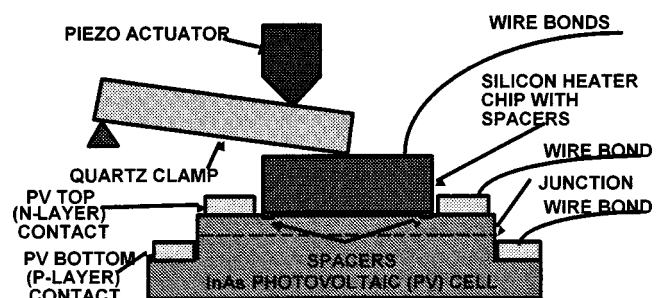


FIG. 1. Schematic of the experimental configuration illustrating the relative positions of the heater chip and thermophotovoltaic (TPV) cell.

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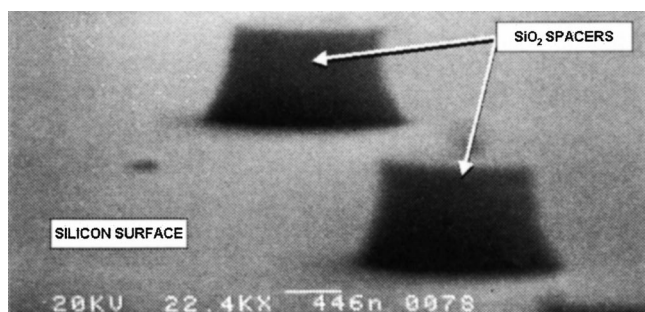


FIG. 2. Scanning electron micrograph of the silicon dioxide, SiO<sub>2</sub>, spacers that separate the main surface of the heater chip from the TPV cell.

The bulk of the heterostructure was grown at 420 °C. The layered structure, beginning at the substrate, consisted of a heavily doped *p*-type buffer layer, 0.3 μm of *p*-type InAs doped with  $1 \times 10^{18} \text{ cm}^{-3}$  Be, 1.0 μm of *p*-type InAs doped with  $2.0 \times 10^{17} \text{ cm}^{-3}$  Be, 16 nm of nominally undoped InAs, and 0.3 μm of *n*-type InAs doped with  $2.0 \times 10^{17} \text{ cm}^{-3}$  Si.

The cells were etched-mesa structures with contacts to the *n* and *p* layers of the photovoltaic cell made in ring fashion to leave a featureless area in the center of the cell so that the ability to place the heater chip in submicron proximity to the surface of the TPV cell would not be obstructed.

The heater chip and photovoltaic cell shown in Fig. 1 were assembled as shown in Fig. 3. The cold side of the assembly consists of the photovoltaic cell mounted on a brass block, which is mounted on a thermoelectric cooler, which is mounted on a liquid cooling block. All are attached with thermal vacuum grease. The heater chip is held in place on top of the photovoltaic cell by a mechanical spring-loaded clamp. The heater chip and the photovoltaic cell are wire bonded to the modified flatpack chip carrier shown. Contacts are brought out from the photovoltaic cell and the following components on the heater chip: heater element, temperature sensor, and capacitive contact.

The heater/photovoltaic cell assembly was placed in a bell jar with the liquid chiller outside. A small turbopump was used to provide the vacuum in the 40 mTorr range. A surface-mounted thermocouple was used to monitor the brass mounting block temperature, which was used as the approximate photovoltaic (PV) temperature. All electrical and thermocouple contacts were brought out through vacuum feedthroughs. The cover to the bell jar was a lexan plate with

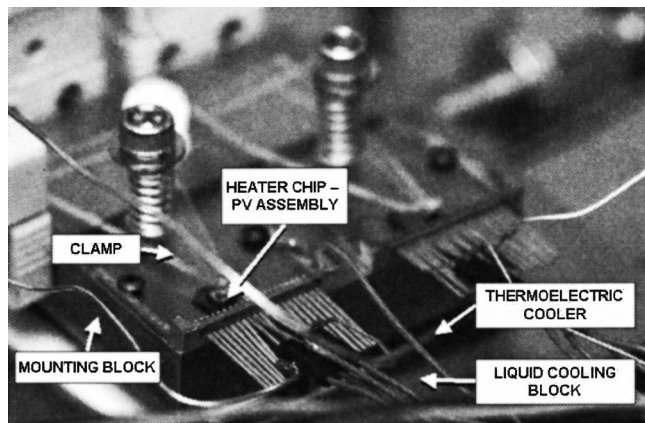


FIG. 3. Heater chip and thermophotovoltaic cell assembly.

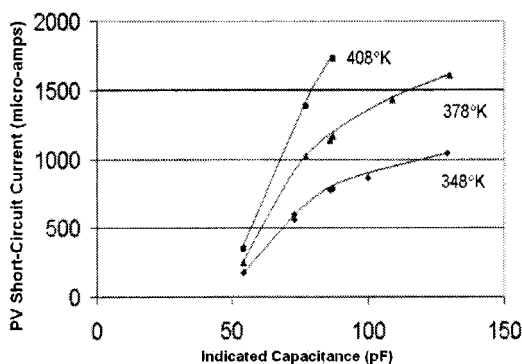


FIG. 4. Static test results: variation of photovoltaic short-circuit current with capacitance between the heater chip and the photovoltaic cell.

an o-ring seal. The piezoelectric actuator was mounted on a manually adjustable linear feedthrough that was mounted through the vacuum cover.

The initial gap was estimated by measuring the capacitance between the heater chip and the PV chip. An HP 4275A LCR meter was used. Guarding and ground isolation allowed simultaneous heater, PV current, and capacitance measurement. The resistance of the 180 Ω on-chip Pt resistor measured the heater temperature. The PV short-circuit current was measured using a Keithly 485 picoammeter. Its analog output allowed simultaneous display with the piezodriven excitation discussed below. An MDC K075 piezotransducer was driven with an offset sine wave from a TeK PG504 function generator. The quartz clamp lever arm ensured electrical isolation of the 20 V *p-p* piezo excitation from the output measurement.

The results shown in Fig. 4 were produced by the following procedure. The piezoelectric actuator was brought into contact with the mechanical clamp from above, as depicted schematically in Fig. 1. Contact was sensed by an increase in capacitance. The capacitance, heater chip temperature, and PV short-circuit current were recorded. The piezoactuator was then extended further, thereby flexing the heater chip by fractions of a micron, thereby decreasing the gap and increasing the capacitance. Upon decreasing the gap, two observations were apparent immediately—the short-circuit current increased and the temperature of the heater chip decreased. Both are explained by the increased coupling of energy across the gap. In order to obtain constant temperature data, the power to the heater was increased to maintain the initial temperature. The capacitance and photovoltaic short-circuit current were also recorded. Data were taken for the three temperatures indicated in Fig. 4, with multiple cycles among the temperatures with repeatable results. As shown in Fig. 4, there is a very strong relationship between gap and short-circuit current over the range of measurements.

In addition to these static tests, a dynamic test was also performed to clarify the possible influence of stray thermal effects accounting for the current increase. The piezoactuator was oscillated up and down between frequencies of 200 and 1000 Hz, which are beyond the frequency that thermal effects would be able to follow. The oscillating piezo was then brought into contact with the heater chip clamp, causing it, and therefore the gap, to oscillate. If the current were due to

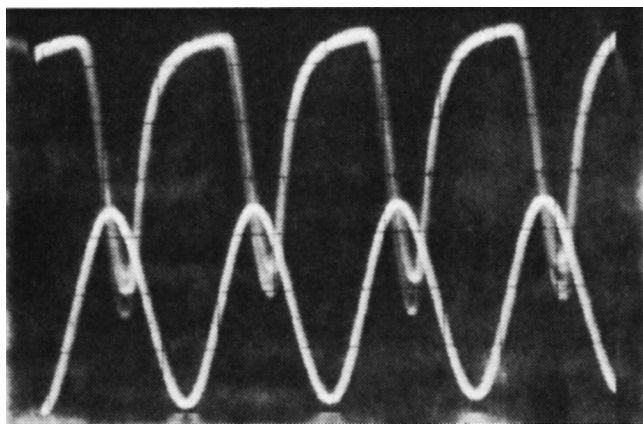


FIG. 5. Dynamic test results: 200 Hz oscillating piezo drive voltage (bottom curve, increasing voltage is up) and corresponding oscillating photovoltaic short-circuit current (top curve, increasing current is down).

thermal effects, it would not be able to follow the gap oscillation frequency and the short-circuit current would not be modulated by it. The in-phase nature of the response supports the arguments against a thermal effect (see Fig. 5).

It is possible that more than one coupling mechanism is present. Pan and co-workers<sup>14,15</sup> have described one mechanism for the enhanced carrier generation. Photons generated inside the heated emitter solid and proceeding toward the interface of the heated emitter surface and the vacuum gap microcavity, which would with a large gap experience total internal reflection, are enabled instead to proceed through the vacuum gap and into the cool photovoltaic cell because of its close proximity. An excellent presentation of this phenomenon is also found in Feynman.<sup>18</sup> Near-field effects, in addition to other energy transfer mechanisms, may also be responsible for the enhanced carrier generation observed here and/or may be observable in similar nonisothermal vacuum microcavities.

In conclusion, we have experimentally demonstrated enhanced coupling between a heated surface and an electronic device resulting from submicron spacing between the two surfaces. This has been shown by a correlation between a

factor of 5 increase in the photovoltaic short-circuit output and the capacitance between the two devices.

It would be premature to infer detailed quantitative data from the current measurements. Present data demonstrate the effect but do not quantify it. Measurements are underway to obtain more quantitative data. By demonstrating the use of a nonisothermal microcavity to achieve the results described herein, it is hoped that an active area of research will develop to fully characterize and use the physics of nonisothermal microcavities for energy conversion applications, including, but not limited to TPV, where it is believed to have a significant impact.

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