Microfabricated Silicon Carbide Thermionic Energy Converters for Solar Energy Generation

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Abstract:

Microfabricated thermionic energy converters (TECs) could be a crucial candidate for concentrated solar thermal power plants. TECs convert heat directly to electricity. They can therefore be thought of as heat engines in which the working fluid is electrons themselves. Electrons are "boiled" off the hot cathode and then condensed and absorbed at the cooler anode: the temperature difference produces a voltage between the cathode and anode. This study explored the fabrication of silicon carbide (SiC) cathodes (emitters) with integrated SiC anodes, i.e., complete converter structures. The fabrication process involved wafer bonding, reactive ion etching to pattern the structures, and vapor HF releasing to suspend the cathodes (emitters). We fabricated the devices with a 1.7 μm gap between the cathode and anode, with a yield of over 50%. Using resistive heating, we measured the thermionic current. Later, we will use laser heating to demonstrate the first microfabricated TECs and measure the conversion efficiency to explore future use in clean energy production.

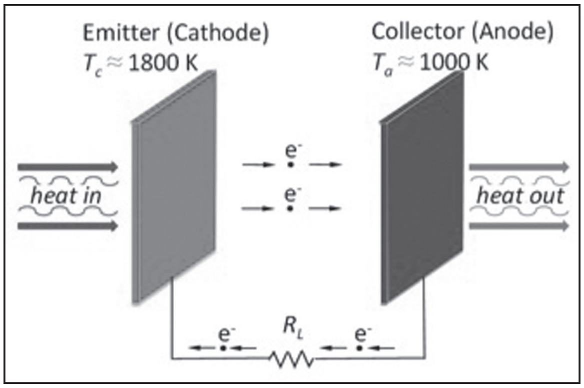

Figure 1: A simplified diagram of a TEC.

Introduction:

Thermionic energy converters (TECs) have three main components: cathode (emitter), vacuum gap, and anode (collector). Figure 1 shows a simplified diagram of a TEC. The cathode is typically at a temperature greater than 1500°K and the anode is typically less than 1000°K. In the hot cathode, electrons with energy greater than the work function escape into vacuum and are collected at the cooler anode [1]. In the past, TECs developed on the macro-scale had only 10-15% efficiencies [1]. Yet, microfabricated TECs are potentially a more cost-effective and efficient means of producing clean energy as a component of concentrated solar thermal power generators. Microfabricated TECs have the potential for 30-40% efficiencies [1].

One way of increasing efficiency is to reduce the size of the vacuum gap to diminish space charge. In practice, however, it is challenging to create a structure stable and effective under the necessary temperatures. Potential problems can arise due to the stress of thermal expansion. Radiative heat transfer from the cathode to the anode can also decrease efficiencies.

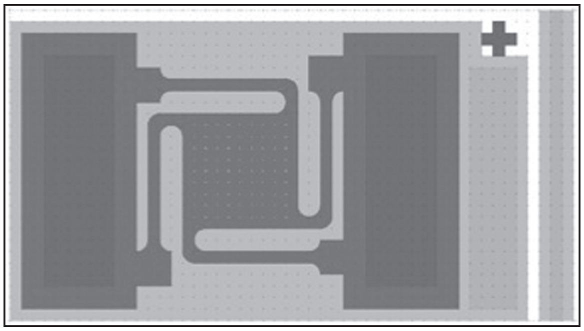

Figure 2: TEC structure with a SiC cathode center pad surrounded by legs that connect to contact pads.

Here we report the fabrication and detection of thermionic current from a micron-scale TEC with an integrated silicon carbide cathode and anode. The TEC structure is a SiC cathode center pad surrounded by legs that connect to contact pads and are suspended 1.7 μm above a SiC layer that forms the anode (see Figure 2).

This study used *n*-type SiC and so will enable comparison with future *p*-type TECs. Test structures were varied: legs ranged from 25-100 μm and center pads ranged from 500 to 800 μm. Legs serve to thermally isolate the center pad and provide stability under thermal stress. Etch holes in the center pad allow vapor HF release of the cathode.

Experimental Procedure:

The fabrication process began with deposition of the following layers on a Si substrate: thermally grown oxide (1.7 μm), SiC (2 μm), low temperature oxide (LTO, 1.7 μm), SiC (2 μm), LTO (1.8 μm), and photoresist (1.7 μm).

First, we patterned the photoresist and LTO layers with reactive ion etching (RIE). After removing the photoresist to reduce surface roughness, the first SiC layer (cathode) was etched using RIE. The LTO layer was then patterned using a BOE 6:1 isotropic etching. Gold contact pads were created by first spinning photoresist, patterning photoresist, evaporating gold, and using an acetone lift-off to leave gold contacts to the cathode and anode. Finally, the cathode was released from the anode using vapor HF etching. The final yield of fully released structures was over 50%. The structure of the final devices included an ~ 1.5 μm SiC center pad and legs suspended above a SiC anode layer connected to the silicon substrate via a thermally grown oxide isolation layer.

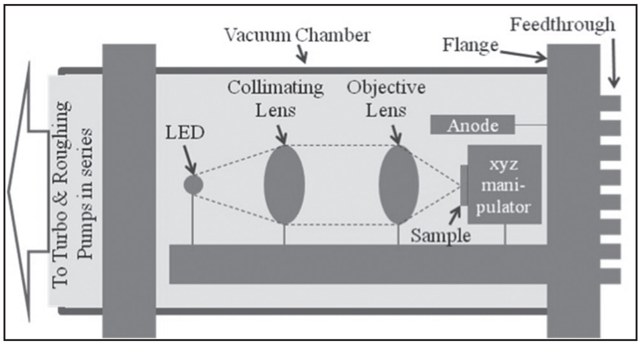

Figure 3: Vacuum chamber diagram.

Testing of devices was done in a vacuum chamber (see Figure 3 for vacuum chamber diagram [2]). The cathode was biased on one side to -16V and connected to ground at the opposite side, leaving the center pad approximately 8 V. The anode voltage was then varied from -20V to16V.

Results and Conclusions:

Figure 4 is a graph of the anode current as the anode voltage was varied: first no current flowed until ~ 8V, whereupon current began to increase with increased anode voltage. The current continued to increase as the voltage was increased and did not reach the expected plateau. This enhancement was because the device was biased, and so the electric field produced field-enhanced thermionic emission called "Schottky emission" in which the electric field lowered the energy barrier for electrons to escape into vacuum. Although the devices were effective, there was vertical bowing of the cathode under thermal stress, and so the true gap size is uncertain.

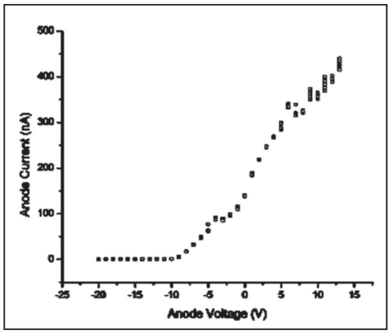

Figure 4: Graph of the anode current as the anode voltage was varied.

Future Work:

Future experiments will include testing with laser heating instead of resistive heating in order to obtain a conversion efficiency without biasing the device. To overcome vertical buckling, future structures will be fabricated using a vertical wall pattern to enhance stability under high temperatures. Methods of producing thicker cathodes will further stabilize the structure. Continued fabrication efforts will be focused not only on SiC, but also on different materials. Finally, in the future devices will be fabricated to include vacuum encapsulation in a quartz or sapphire layer to facilitate mass production and use in energy generation.

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References:

[1] National Research Council Committee on Thermionic Research and Technology. Thermionics Quo Vadis? An Assessment of the DTRA's Advanced Thermionics Research and Development Program (National Academy 2001).

[2] J.-H. Lee et al., "Effect of illumination on thermionic emission of microfabricated silicon carbide structures," 16th Int. Conf. on Solid-State Sensors, Actuators, and Microsystems (Transducers '11), Beijing, China, June 5-9, 2011, pp. 2658-2661.