

FINAL REPORT

to the

OFFICE OF NAVAL RESEARCH

for a Program on

THERMIONIC COOLING DEVICES

For the period March 1, 1998 to September 30, 1999

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Long-Term Research Objective

The long-term objective of this project is to investigate the feasibility of thermionic cooling technology based on micromachined structures with controlled gaps and potentials. Success will depend on identification of a suitable micromechanical test structure, suitable electrode materials, and a series of experiments which can identify the emission mechanism and detect thermal transport.

Science and Technology Objectives

The Science and Technology objectives are:

- o Demonstrate thermionic emission in a tunable micromechanical structure.
- o Experimentally study the relationships between gap, potential, temperature, and electrode materials and the emission phenomena.
- o Provide a preliminary design for a new cooling technology.

Approach

Stanford University has in-house expertise in materials characterization, and microstructure fabrication. A particular microstructure already developed at Stanford allows independent control of gap and potential between a pair of metallic electrodes over a range of gap and potential values that should be suitable for thermionic emission. Through collaboration with B. Moyzhes, we have experience with materials and technologies for emitters.

Our proposed approach is to combine this materials expertise and microstructure fabrication expertise to build a series of simple test structures with the appropriate materials for an experiment to test the behavior of thermionic emission. We will study the relationships between materials, gaps, emission current, and thermal transport to determine if a useful technology might be accessible.

Science and Technology Completed

During this program, we have completed the following activities :

- 1) Characterized the work functions of electrode materials available within the constraints of the MEMS fabrication approach. We studied Au and Nb films with and without O₂ implantation and Cs film coatings. We found that we could consistently achieve work function values in the range of 1.2-1.3 eV on Nb surfaces and Au surfaces coated with Cs.
- 2) Fabricated a series of micromachined silicon device structures which featured silicon nitride membranes and fixed pyramidal tips that were coated with Au and Nb films. These devices are fabricated in quantities of 100 or more using a novel wafer-scale fabrication and bonding process. During the period of this project, this bonding process became unreliable, and considerable effort on another contract was diverted to characterize and solve this problem. In addition, it became clear that Nb films were becoming contaminated by the underlying Ti adhesion layers at the 350C bonding temperature, so we substituted Pt films in these devices. Finally, we successfully bonded a large quantity of Au and Pt electrode devices.
- 3) Analyzed the exact shape of tunneling barriers and extracted numerical predictions for tunneling, field emission and thermionic emission as a function of electrode work function, bias voltages, and electrode gaps. This work was based on the analysis published by Simmons (John G. Simmons, "Electric Tunnel Effect Between Similar Electrodes Separated by a Thin Insulating Film," *Journal of Applied Physics*, Volume 34, Number 9, p. 2581 (1963)). Initially the analysis indicated that favorable thermionic currents could easily be obtained with the spacings available in the membrane structure and with the work functions of Cs-coated Au and Pt. However, we have discovered an error of a factor of 1/2 in the calculation of the image-charge correction to the barrier height. This error is important, because it lowers the value of the work function required for measurable thermionic emission. Even so, the barrier height is effectively reduced by a narrow gap, so that instead of a work function of 0.4 eV which is required for a conventional gap geometry a value of 1.0 eV will produce useable cooling. This is an important result of our investigation because work functions of 1.0 eV have been obtained in many previous cases. Our results are being submitted for publication in *Appl. Phys. Lett.*

4) Performed experiments to characterize the current emitted from these electrodes as a function of bias voltage and tunneling gap for Au and Pt films with and without Cs overlayers. We have recorded tunneling currents over a wide range of these conditions at levels consistent with our models, and have observed appropriate variations in tunneling current with electrode material and Cs coating. We have also noticed instabilities in the current for periods of time as long as a day after Cs exposure, indicating that these films are not stable on these electrodes, and that a steady vapor pressure may need to be maintained for stable operation. With the present electrodes which have work functions of 1.3 –1.4 eV we have observed tunneling currents but have as yet no evidence for thermionic currents. We believe that these results are consistent with our model for the barrier which properly accounts for the image charge corrections, and that it will be necessary to develop devices with lower work functions of the order of 1.0 eV to observe thermionic emission.

Impact/Navy Relevance

This research project is potentially very significant. Thermionic emission has the potential to offer efficient energy conversion and cooling devices for small-scale and large-scale applications that is superior to the solid thermoelectric devices. There is a great need for enhanced efficiency conversion and cooling devices throughout the technologies of interest to DOD. *The present small-scale effort demonstrates that spacing of the electrodes at distances of the order of 100 Å is feasible, and that at this spacing the required work function is increased from an impractical value of 0.4 eV to a realistic value of 1.0 eV.*

Planned Research Efforts

We hope to continue this work by exploring other electrode materials including AgO and some novel semiconductors. Because this remains a single-PhD student project, an appropriate level of funding is \$90K/year, and would allow us to continue making progress on electrode materials, MEMS device design, and measurements. We have already constructed all the necessary measurement apparatus, and expect to continue benefiting from access to the wafer-scale manufacturing process at IC Sensors in Milpitas.

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14. ABSTRACT The work functions of Au and Nb films with and without O2 implantation and with Cs film coatings were measured. Work functions with values in the range of 1.2-1.3 eV on Nb and Au surfaces coated with Cs were measured. A series of micromachined silicon device structures which featured silicon nitride membranes and fixed pyramidal tips suitable for measuring thermionic currents were fabricated. Numerical predictions for tunneling, field emission and thermionic emission as a function of electrode work function, bias voltages, and electrode gaps made using Simmons model showed that thermionic cooling should be achievable with reasonable parameters. However an error of a factor of 1/2 was found in Simmon's calculation of the image-charge correction to the barrier height which reduces the requirement for the work function from about 1.3eV to about 0.9-1.0 eV. No evidence for thermionic currents was observed using Au and Pt electrodes with or without Cs overlayers as expected for the experimental conditions with the modeling based upon the corrected formula.					
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