Cooling and Power Conversion using Nanometer Gaps

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ABSTRACT

The enormous potential of solid state cooling and the direct conversion of heat into electricity has long been recognized, but despite the many benefits in terms of size, weight, design simplicity and reduced environmental impact, widespread adoption has been limited in large part because of the low efficiency and high cost of available technologies.

Our research has resulted in a new diode design that relies on electron tunneling through a nanometer-scale vacuum gap as its primary operating mechanism. Experiments to date have resulted in consistent production of devices with conformal electrode surfaces, with measured electron tunneling currents in excess of 10A through the vacuum gap. Now, after having successfully resolved the primary technical challenge of creating and maintaining the vacuum gap between the electrodes, research efforts can be focused on the remaining engineering tasks on the path to commercialization. These tasks include integrating low work function materials during electrode fabrication and finalizing package design and assembly.

Potential applications span a broad spectrum ranging from aerospace to automotive, refrigeration and HVAC systems. Once development is complete, these devices are expected to offer high-performance, low-cost replacements for just about any existing cooling or power generation solution at efficiencies far greater than thermoelectric alternatives.

Keywords: electron, tunneling, vacuum, Cool, Power

1 INTRODUCTION

A number of recent research projects have examined the potential of electron tunneling for cooling and power generation applications. Superconductor-Insulator-Normal metal (SIN) junctions have been used for cooling at low temperatures[1]. Other devices have been constructed using a Superconductor – Insulator – Normal metal – Insulator – Superconductor (SINIS) structure[2]. Additionally, calculations of cooling were made for Normal metal-Insulator-Normal-metal (NIN) tunnel junctions[3]. In all of these cases, tunneling takes place through an insulator layer between two metals. Because of the high thermal conductivity of thin insulator layers, the effectiveness of these devices is limited. One solution to the heat backflow problem using multiple tunnel junctions of NIN type in series was offered by Korotkov et. al.[4] but the complexity of multiple junction fabrication prevented further development.

Our research has resulted in a new structure, described as a Normal metal-Vacuum-Normal metal (NVN)[5] junction. A key advantage of this structure is the use of a vacuum as the insulator. The vacuum layer offers formally zero heat conductivity between the electrodes, allowing the fabrication of tunnel junctions with extremely low thermal backflow. These tunnel junctions represent a means of creating high-efficiency cooling and power generation, and have begun to draw greater interest. Independent of our own work, theoretical research at Stanford University examined these structures[6] in detail. Other methods of using a vacuum gap, in one case utilizing emission from semiconductor resonant states, have also been investigated[7].

Most cooling and power generation applications require tunnel junctions with a sufficiently large area (on the order of several square centimeters) to provide useful levels of performance. Fabricating NVN tunnel junctions with large areas poses several practical problems. The electrodes for such junctions should be flat within tens of Angstroms across a large area, without any areas of excessive local roughness . State of the art polishing methods allow for the fabrication of surfaces with a flatness of 0.5 micron per centimeter, which is still two orders of magnitude greater than what is required. The local roughness of polished surfaces available today is low enough (as low as 5 Angstroms) to allow tunneling through the vacuum gap, but because of slight deviations in the surfaces it is not possible to bring large areas of two electrodes (polished independently) close enough to each other to allow tunneling to take place. To solve this problem, we have developed a method of fabricating pairs of electrodes in which the topographical features are precisely matched. With a matched electrode pair, proximity can be maintained without perfect flatness.

2 ELECTRODE FABRICATION METHOD

To fabricate the pair of electrodes, we begin with a doped Si wafer as the substrate. A 0.1 micron thick Ti film is first deposited over the Si substrate (fig. 1a). Next, a 1 micron thick Ag film is deposited over the Ti layer. Deposition regimes for Ag are chosen to optimize adhesion of Ag to the Ti film (For our purposes, the optimum adhesion is much lower than typical microelectronics

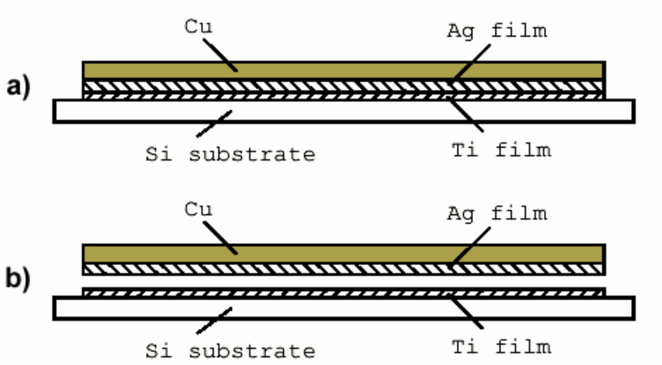


Figure 1. a) Si/Ti/Ag/Cu sandwich, b) Opened sandwich with conformal electrode surfaces.

processes). Finally, a layer of Cu 500 microns thick is grown electrochemically on the Ag film.

The "sandwich" can then be opened on the border of Ti and Ag films (fig.1b). Low adhesion between the Ti and Ag films allows the sandwich to open without significant deformation of the electrodes. After separation, we are left with two conformal electrodes that allow for tunneling over broad areas of the electrodes.

The sandwich is opened in a sealed chamber with the atmosphere evacuated to avoid oxidation of the sample. The sandwich is opened either by cooling or by heating. Because Cu and Si have different Thermal Expansion Coefficients (TEC), the two electrodes separate from the slight mechanical stress induced by the temperature change. As observed earlier, the adhesion between the Ti and Ag films must be low enough to allow the sandwich to open without creating deformation in the electrodes. It is important, however, that the adhesion be high enough to prevent electrochemical liquid from penetrating between the films during the electrochemical growth of the Cu layer. Precise adhesion control between the Ti and Ag films is therefore critical.

Tunneling current between two electrodes increases significantly at distances less than 100 Å[5]. To control the width of the gap, the experimental device uses two-stage regulation. The first stage is mechanical, using a differential screw to regulate the distance within a few microns. The second stage is a piezoelectric cylinder with resolution on the order of 1 Å. Four two-stage regulators are used, with one regulator placed in the center of the round Cu electrode and three regulators placed equilaterally on the perimeter of the Cu electrode. These regulators enable the changing of the distance and angle between the electrodes during the measurements.

Another method for distance regulation is the use of dielectric spacers between the electrodes. Al_2O_3 spacers can be deposited using reactive DC magnetron sputtering of Al. Al_2O_3 is deposited on the Ti film before the deposition of the Ag film (not shown on fig. 1). Porous Al2O3 is used to minimize the thermal conductivity of spacers. After opening the sandwich, the spacers remain on the Ti film because of their low adhesion to Ag. The spacers prevent the electrodes from short-circuiting.

Capacitance and conductance between the electrodes are monitored during these experiments. The capacitance readout is used to determine the mean distance between the electrodes, and the conductance readout is used to determine the total area of the shorts between the electrodes. I-V characteristics of the junctions are recorded to detect tunneling currents.

3 EXPERIMENTAL RESULTS

The primary obstacle in the creation of conformal surfaces is the deformation of the electrodes. Interferograms like those shown in figures 2 and 3 (below) were taken at each stage to trace the sources of mechanical tension in the electrodes. The electrode pair in figure 2 shows some conformity, but there is still considerable variation in the interferograms of the Si/Ti and Cu/Ag electrodes. By selecting silicon wafers with reduced surface curvature and reducing the tension in the Cu/Ag electrodes, we were able to produce electrode pairs with significantly lower surface curvature and increased conformity between electrodes. Figure 3 shows a recent electrode pair, demon-

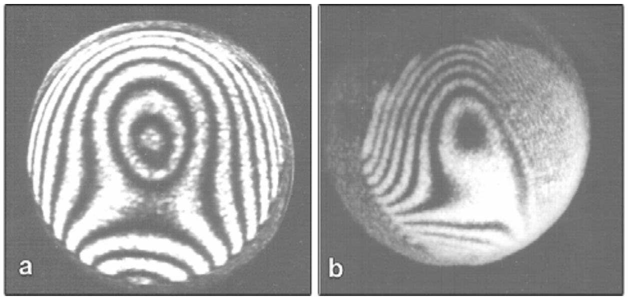


Figure 2. Interferogram showing the curvature of an early electrode pair, a) Si/Ti and b) Cu/Ag . Distance between rings: 317 nm. Electrode diameter: 28 mm.

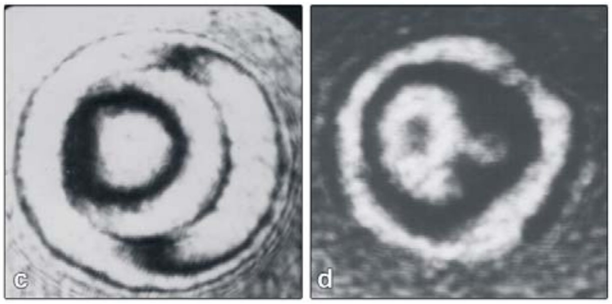
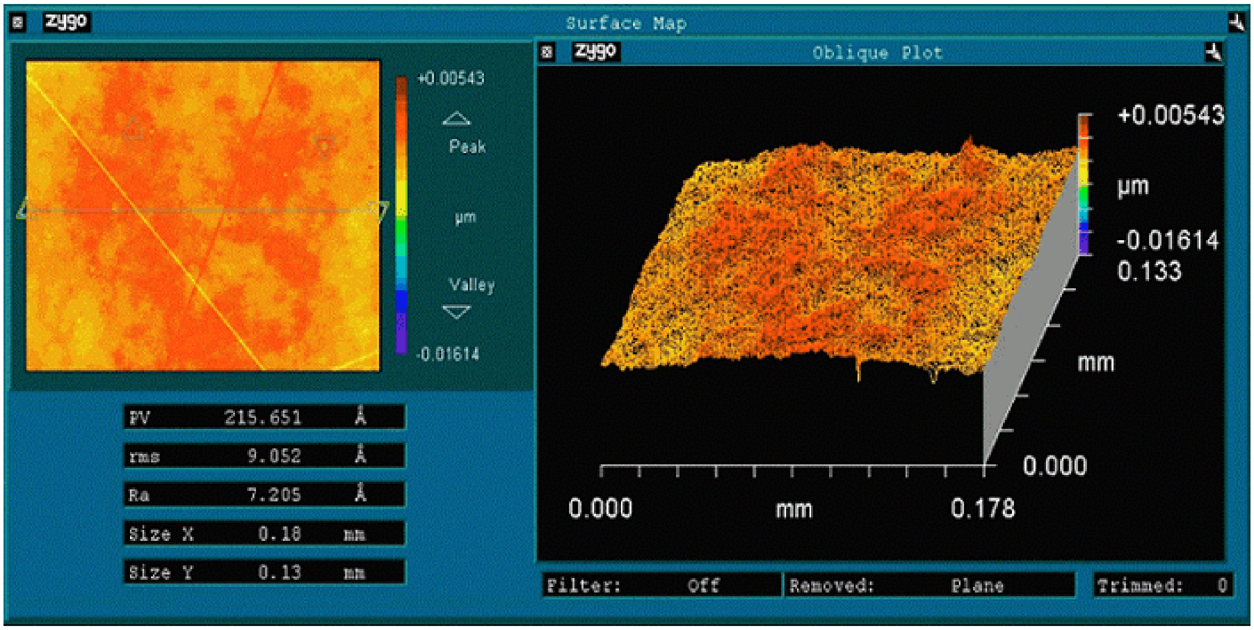


Figure 3. Interferogram showing the curvature of a more recent electrode pair, c) Si/Ti and d) Cu/Ag . Increased flatness is visible in the reduction in contour lines.



PV 215.651 Å
rms 9.052 Å
Ra 7.205 Å
Size X 0.18 mm
Size Y 0.13 mm
Filter: Off
Removed: Plane
Trimmed: 0

Figure 4. 3-D plot of a 0.18mm X 0.13mm area of the Cu/Ag electrode.

strating both the reduction in curvature and the close conformity of the curvature between the electrodes.
To analyze local roughness of the surfaces of the electrodes we recorded profilograms of the surfaces of the electrodes. Detailed examinations of surface roughness were conducted by a potential commercial partner. Local roughness measurement results of a Cu/Ag electrode are presented in figure 4 (below).

Figure 4 shows that the electrode surface is extremely smooth, with an average roughness of 7.2Å. In fact, because of the extremely low observed roughness of the electrode surface it was suggested that the measuring equipment should be recalibrated to verify the measurements taken. After performing tests with a Silicon Carbide reference flat, measurements were retaken and the results confirmed.

Device Sample	Capacitance (µ F)	Conductance (mS)	Average Distance (Å)
1	0.56	42	107
2	0.49	10	122
3	0.38	445	157
4	0.30	300	200
5	0.23	327	260
6	0.11	214	545

Table 1. Capacitance, Conductance and Average Distance between the electrodes of selected samples.

In Table 1, capacitance, conductance, and mean distance between electrodes of six samples are shown. The first two are samples which demonstrated superb C/G ratios. Samples 3-6 have typical C/G ratios. Average distances between electrodes were a few hundred Angstroms.

The I-V characteristics of closed sandwiches were linear, with a resistance of less than 0.5 mΩ. When opened, I-V characteristics became nonlinear as a result of tunneling , with changes to both shape and slope as distance was regulated. All the I-V characteristics we recorded show that the main component of current comes from electron tunneling, with remaining current coming from conduction through any shorts between the electrodes (conducted current being proportional to the applied voltage).

At high applied voltages (1-5 V, depending on the sample) the electrostatic attraction between the electrodes in some cases "closed" the sandwich with a measured attraction force in the range of 4-6 kg. After releasing the sandwich by switching off the applied voltage it remained closed, and only opened after additional distance regulation was applied. In order to prevent unwanted closure and avoid a short circuit between the electrodes, Al2O3 spacers 100 nm and 50 nm in height were tested. With 100 nm spacers a threshold voltage approaching 5 V was obtained, but ridges on the surface of the Al2O3 were observed under an optical microscope. Reducing the thickness of the spacers to 50 nm eliminated the ridges, and yielded a maximum threshold voltage of 3 V.

4 COMPLETING DEVELOPMENT

Work currently underway in several areas must be completed before commercial prototypes can be produced. In addition to further process refinements to reduce the likelihood of electrode deformation, packaging work and integration of cesiated materials into electrode surfaces remains.

In order to get useful cooling and power generation effects at room temperature, the work function of the electrodes must be reduced to 1-1.5 eV by incorporating cesium into the electrodes. The influence of Cs on both Ti and Ag materials is well understood, with work functions of 1-1.5 eV having been achieved[8].

Package designs under consideration use piezoelectric materials both as a means to regulate the gap width and as a seal against atmospheric contamination. For applications with high power generation or cooling requirements, this package design allows for scalability using arrays of devices over a larger area.

The most challenging work, creating and maintaining the gap between electrodes, has been completed. Although refinements may occur to the remaining process steps, we are consistently able to produce electrodes with conformal surfaces and uniformly low local roughness. Once we have completed the integration of cesiated materials, we expect to begin detailed performance analysis. Evaluation devices should then become available to commercial partners once packaging designs are finished.

5 CONCLUSION

After completing development, we expect the impact of this technology to be far-reaching across many areas of thermal management and power generation. Many aerospace applications, for example, have size and weight constraints that would make these compact, high efficiency devices an ideal solution. From esoteric applications like improved radioisotope power generation or cooling sensitive infrared detectors, to more mundane applications like refrigerators and automotive power and cooling, solutions based on electron tunneling across a vacuum gap hold great potential.

Furthermore, because the materials used are both inexpensive and readily available, and because there are relatively few production steps involved, we anticipate that mass-production should be feasible and that mass-produced devices should be inexpensive compared to alternative solutions. Even without the benefits stemming from improved performance and a small, low maintenance form factor, the projected cost advantage alone makes this technology worth pursuing for the next generation of cooling and power generating solutions.

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