Electron Tunneling Through Large Area Vacuum Gap -- Preliminary Results

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Abstract

We have obtained tunneling currents of over 10 A through the vacuum gap between conformal electrodes having an effective area on the order of 0.1-1 cm^2. The large area vacuum gap is obtained by using a surface replication method that allows for two electrodes to have precisely matched topographies. The width of the vacuum gap within the range of 30-100 Å is regulated using piezoelectric actuators. These same actuators are used to regulate angles between the electrodes. Measured I-V characteristics show that the overall current through the system can be represented as the sum of the tunneling current and the current running through the short circuits between electrodes, and that tunneling current becomes dominant at distances greater than 30 Å. The dependence of the capacitance and conductance on the distance between electrodes is in good agreement with the simple model of electrodes separated by a vacuum gap. Such an electron tunneling device could be used for cooling and power generation, as well as for other applications.

Introduction

In recent years, some work has been done on using electron tunneling for cooling and power generation applications. Superconductor-Insulator-Normal-metal (SIN) junctions are used for cooling at low temperatures [1]. Additionally, calculations of cooling were made for Normal-metal-Insulator-Normal-metal (NIN) tunnel junctions [2]. In both cases, tunneling takes place through an insulator layer between two metals. Because of the high thermal conductivity of thin insulator layers, those devices cannot achieve effective cooling. One solution to the heat backflow problem, using multiple tunnel junctions of NIN type in series, was offered by Korotkov et. al. [3] but unfortunately the idea was not realized because of the complexity of multiple junction fabrication. We have developed tunnel junctions of a new type which comprise Normal-Vacuum-Normal metal (NVN) [4]. A key advantage of our junctions is the use of a vacuum as the insulator. Consequently, there is formally zero heat conductivity between the electrodes, allowing the fabrication of tunnel junctions with extremely low thermal backflow. Such tunnel junctions could be used for effective cooling and power generation. Independent of our own work, a theoretical group at Stanford University was working in the same direction [5]. Another method of using a vacuum gap utilizing emission from semiconductor resonant states was proposed in [6].

Most cooling and power generation applications require tunnel junctions with a large area — on the order of square centimeters. Fabricating tunnel junctions of type of NVN with large areas has practical problems. The electrodes for such junctions should be flat within tens of Angstroms across a large area. 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 required. With such surface roughness present, it is impossible to bring two polished electrodes close enough together for tunneling to take place over the entire area. On the other hand, the local roughness of polished surfaces available today is reduced, going down to 5 Angstroms. The local roughness of the electrode surface is low enough to use tunneling through the vacuum, but because of a gradual deviation in the surface relief over large distances (caused by polishing methods) it is not possible to bring large areas of two electrodes (polished independently) close enough to each other. To solve this problem, we have developed a method of fabricating pairs of electrodes in which the topographical features of one electrode are matched in the other.

Electrode fabrication method

To fabricate the pair of electrodes a doped Si wafer is used as the substrate. The dopant is n type, and the conductivity of the doped Si is on the order of 0.05 Ohm cm. A 0.1 micron thick Ti film is deposited over the Si substrate using DC magnetron sputtering method (fig. 1a). A round metallic mask with a diameter of 28 mm is used for the Ti film deposition. After deposition, the Ti is backed with Si to achieve maximum adhesion of the Ti film to the Si substrate. The next step is the in situ deposition of 1 micron thick Ag film using the same method. Deposition regimes for Ag are chosen to achieve optimum adhesion of Ag to the Ti film (The optimum adhesion is much less than the adhesion usually used in microelectronics processes). A layer of Cu 500 microns thick is grown electrochemically on the Ag film. The Cu is grown using the ordinary electrochemical growth. Then the sandwich on the border of Ti and Ag films is opened (fig.1b). Once we have low adhesion between the Ti and Ag films, the sandwich opens without considerable deformation of the electrodes. In this way, two conformal electrodes are fabricated. With conformal electrodes it is then possible to achieve tunneling currents over broad areas of the electrodes.

In the technological process, we use metallic masks to define the shape of the films. We do not use lithography to avoid exposing the samples to the atmosphere. This simplifies sample preparation and avoids problems connected with the cleaning of the electrode surfaces. Although it creates some problems later with electrochemistry, our experiments show these problems are easier to solve.

The sandwich is opened after the sandwich is placed in a sealed area, and it is pumped down. By not exposing the electrode surfaces to the atmosphere, oxidation is avoided. The sandwich is opened by cooling it down in a vacuum from room temperature to approximately 0°C or heating it up to 40°C. Because Cu and Si have different Thermal Expansion Coefficients (TEC) the two electrodes separate in the process of cooling or heating. If the adhesion between the Ti and Ag films is low enough, the sandwich opens without leaving considerable deformation in the electrodes. On the other hand, the adhesion of Ag to Ti must be high enough to prevent electrochemical liquid from entering between the films during the electrochemical growth of Cu. Precise adhesion control between the Ti and Ag films is therefore important.

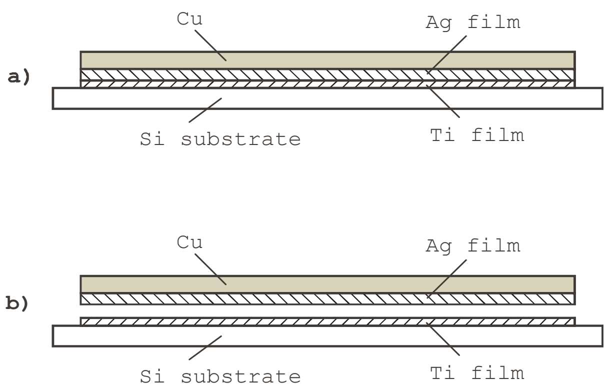

Figure 1. a) Si/Ti/Ag/Cu sandwich, b) Opened sandwich comprising Si/Ti and Cu/Ag electrodes having conformal surfaces.

Tunneling current between two electrodes becomes considerable at distances less than 100 Å [5]. Ideally, the vacuum gap of that width should be maintained between the electrodes. The experimental device uses two-stage regulation of the vacuum gap width. The first stage is mechanical and comprises a differential screw with a pitch of 50 microns. This allows the regulation of the distance within a few microns. The second stage is electrical regulation comprising a piezoelectric cylinder with resolution on the order of 1 Å. Four two-stage regulators are used to regulate distance and angle between the electrodes. One two-stage regulator is placed in the center of the round Cu electrode and three two-stage regulators are 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. We deposit Al_2O_3 spacers using reactive DC magnetron sputtering of Al. Al_2O_3 is deposited through metallic mask on the Ti film before the deposition of the Ag film (not shown on fig. 1). Porous Al_2O_3 is used to minimize the thermal conductivity of spacers. After opening the sandwich, the spacers remain on the Ti film because of the low adhesion to Ag side. The spacers prevent the electrodes from short-circuiting.

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

Experimental results

Samples were prepared to make opening the sandwich as easy as possible, and we have used the structure shown on fig. 1. The most important parameter is the adhesion between the Ti and Ag films, which is regulated precisely during the Ag film deposition. When the Ag adhesion was too high, the Si wafer broke during the opening of the sandwich. When the Ag adhesion was higher than optimal, the Cu electrode was deformed during the sandwich opening process. Deformation of the Cu electrode was dependent on adhesion, and sometimes the deformation was high enough to be observed visually (the electrode surface is highly reflective). When adhesion was closer to the optimum value, we were not able to observe deformation visually; an interferometer was used to measure the deformation. When the adhesion was lower than optimal, the sandwich would open when it was handled. Finally, if adhesion was too low, an electrochemical liquid entered between the electrodes (between Ti and Ag films) during the process of electroplating.

We used Electron Spectroscopy for Chemical Analysis (ESCA) to analyze composition of the surfaces of the electrodes. Some 0.2-0.5 % of Ag was found on the surface of Si/Ti electrode and there was no Ti found on the Cu/Ag electrode. This data shows that the mixing of Ti and Ag is negligible in most samples.

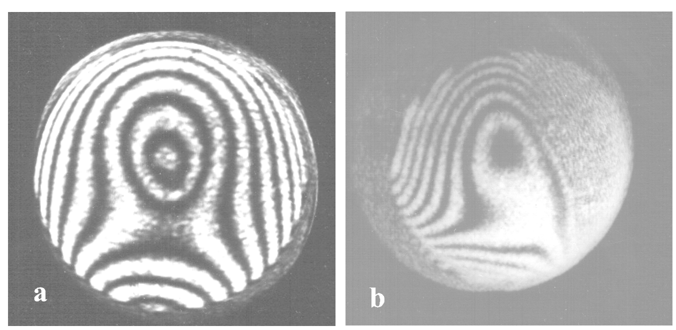

Figure 2. Interferograms of two electrodes, a) Si/Ti and b) CuAg. Distance between the rings: 317 nm. Diameter of the Cu/Ag electrode: 28 mm.

Deformation of the electrodes is the main obstacle in achieving conformal surfaces. Interferograms like that shown in fig. 2 were taken at each stage to trace the sources of mechanical tension in the electrodes. As our experiments show, the sources of tension could be divided in two main categories. The first category is deformation arising during the process of opening of the sandwich. The materials comprising the two electrodes react to mechanical tension in different ways. The bottom electrode (fig. 1) comprises a Si substrate covered with a thin film of Ti. The mechanical properties of the electrode are defined by the Si because the Ti film is too thin to influence the mechanical behavior of the electrode. Si is a hard material and it restores its initial shape after the mechanical tension is released. We observed different behavior on the top electrode, the mechanical properties of which are defined by Cu. Copper is a plastic material and does not restore its initial shape after mechanical tension is released. More precisely, Cu only restores its initial shape with small mechanical tension and does not restore its shape if the mechanical tension is more than a certain value defined by the geometry of the electrode.

The second category of deformation is deformation created in the process of electrochemical growth of the Cu electrode. Cu and Si have different TEC. As a result, if the temperature of the sandwich changes during the growth of Cu, tension between Si and Cu will cause the sandwich to bend as a bimetal does when the temperature changes. A bent sandwich will have more Cu growth and this will become a source of tension in the Cu electrode after the temperature changes again. To avoid this we stabilized the temperature in the bath for electrochemical growth within ±0.1°C. We also found that some tension originated from the mounting of the sandwiches in electroplating baths. Possible sources of tension were analyzed, measured and eliminated.

To analyze local roughness of the surfaces of the electrodes we recorded profilograms of the surfaces of the electrodes.

	Si			**Si/Ti**			**Cu/Ag**		
	Avr	TIR	Ra	Avr	TIR	Ra	Avr	TIR	Ra
1	5	135	20	-230	545	135	385	610	155
2	-65	230	40	-300	610	160	260	445	95
3	30	195	30	-335	550	150	245	435	105
4	-5	130	15	190	305	65	470	740	200
5	-20	170	25	140	220	50	175	385	85
6	55	290	40	160	260	55	85	245	50
7	45	115	15	240	425	95	190	345	75
8	100	200	50	20	145	25	50	215	35
9	-30	170	20	255	485	155	140	240	50
AE	**13**	**182**	**28**	**15.6**	**394**	**99**	**222**	**407**	**94**

Table 1. Profilometer computer data and its average over electrode (AE) for Si substrate, Si/Ti and Cu/Ag electrodes.

2000 micron-long profiles were recorded in 9 places on the surfaces of initial Si wafer and both Si/Ti and Cu/Ag electrodes. We present profilogram data as three values: Avr — which is the average deviation from zero; TIR — which is the peak-to-peak value; and Ra — which is the roughness of the surface (all three are calculated automatically by the profilometer computer). Table 1 shows three numbers in Å for initial wafer surface, for the Si/Ti electrode and for the Cu/Ag electrode. The last row of the table represents Averages per Electrode (AE) which is the mean of 9 values for each column of Table 1. The last row of the table shows that the mean of Avr which is 13 Å for Si does not increase much for Si/Ti which is 15.6 Å. This is natural because the deposition of a uniformly thin Ti film should not influence the average derivation from zero. On the contrary, the same parameter is sharply increased to 222 Å for Cu/Ag electrode which is naturally explained by the bending of Cu/Ag electrode. Another parameter, TIR, is increased from 182 Å to 394 Å after the Ti film deposition. This is easily explained by the granularity of Ti film. TIR did not increase much (407 Å) for the Cu/Ag electrode compared to the Si/Ti electrode. This seems natural, because the peak-to-peak value of conformal films (Ti and Ag) should be similar. The roughness of the Si/Ti electrode is increased from 28 Å on the Si wafer to 99 Å on the surface of the Ti film as a result of the granularity of the Ti film. The 94 Å roughness of the Cu/Ag electrode is very close to the 99 Å roughness of the Si/Ti electrode, which again is easily explained by the fact that roughness of conformal films should be equal.

We monitored the electrical capacitance and electrical conductance between the electrodes during the regulation of the distance between the electrodes. In most cases, we observed an increase in both capacitance and conductance as the distance between the electrodes decreased. For a fixed distance between the electrodes we attempted to increase capacitance by regulation of the angles between the electrodes, and in most cases we were able to increase capacitance considerably through angle regulation. We often noticed that the capacitance-to-conductance ratio for a given sample increased during the process of distance regulation, which is explained by the mechanical destruction of sharp peaks on the surfaces of the electrodes as the electrodes made contact with each other. In Table 2, we present capacitance, conductance, and mean distance between the electrodes for six samples. The first two are samples which demonstrated superb C/G ratios. Samples 3-6 have typical C/G ratios. As seen from the table, we were able to obtain mean distances of a few hundred Angstroms per electrode area. These results are in good agreement with the profilometer data presented in Table 1.

N	C [μF]	G [mS]	d [A]
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 2. Capacitance-C conductance-G and average distance between the electrodes-d of selected samples.

The I-V characteristics of closed sandwiches were linear and seldom showed weak nonlinearity. The resistance of the closed samples was less than 0.5 mΩ. We observed the I-V characteristic while opening the sandwiches. I-V turned from linear to nonlinear when the sandwich was opened, resulting in tunneling I-V characteristics for opened sandwiches (fig. 3). In the process of regulating the distance between electrodes, the I-V characteristics changed both shape and slope. All the I-V characteristics we recorded show that the current through the electrodes has two main components. One component is the tunneling current itself and the other is the current running through shorts between the electrodes. This last component is proportional to the applied voltage. The I-V characteristics often exhibit a hysteresis loop caused by a phase shift in the capacitance between the electrodes. Referring to our experimental results, we can present the equivalent circuit for the sandwich as a tunnel junction connected in parallel with both a resistor and capacitor.

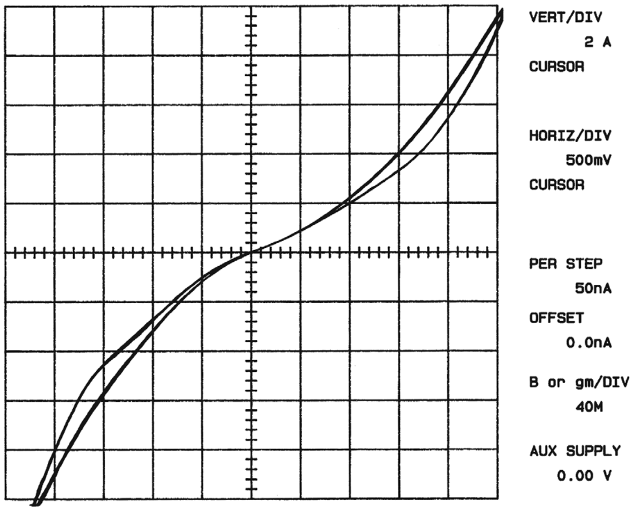

Figure 3. I-V characteristic of the sample after opening and adjusting the distance between the electrodes. Hysteresis loop is due to large capacitance between the electrodes.

In some cases when applied voltage was high enough, the electrostatic attraction between the electrodes "closed" the sandwich. The threshold voltage varied between 1-5 V from sample to sample. The measured attraction force was in the range of 4-6 kg. After releasing the sandwich by switching off the applied voltage it remained "closed" and only after additional distance regulation were we able to open it again.

In order to avoid a short circuit between the electrodes, we used Al_2O_3 spacers 100 nm and 50 nm in height. We measured the threshold voltage of the sandwich after opening the sandwich, in order to determine the quality of the spacers. We were able to approach a threshold voltage of 5 V for the thickness of the spacers on the order of 100 nm. When examining the 100 nm-tall spacer surfaces under an optical microscope we found that there were ridges on the surface of Al_2O_3. Reducing the thickness of the spacers down to 50 nm removed the ridge. The maximum threshold voltage obtained on the 50 nm-tall spacers was 3 V.

Discussion

Because of electrode deformation, the entire electrode area cannot be used for tunneling. Our estimation of the useful area shows that we achieve considerable tunneling only over an area which is less than 10% of the total area. We are working to reduce this deformation and consequently increase the tunneling area. Most of our work is concentrated on reducing the tension introduced during electroplating. Our experiments show that in the case of optimum adhesion, the sandwich opens well, and introduces a tension similar to the tensions originating from other sources. Another avenue of research involves replacing Cu with a less plastic material, such as brass. This, in our opinion, will reduce the remaining tension in the electroplated electrode after opening of the sandwich.

Measurements of roughness and other surface parameters show that electrode surfaces are flat enough for tunneling to take place. In order to improve the electrode surfaces we plan to use Si wafers of better quality and to adjust the Ti film thickness to achieve a better film surface. Reducing the Ti film thickness will decrease the grain size and roughness of the Ti surface. We expect a reduction of roughness 2-3 times better than the results presented in this paper.

We are able to precisely regulate distance between the electrodes and keep the distance between the electrodes constant under influence of vibrations which naturally exist in the laboratory. I-V characteristics together with measurements of C and G show that the primary current between the electrodes is tunneling current.

In order to get cooling and power generation effects at room temperature, we have to reduce the work function of the electrodes down to 1-1.5 eV. This will be done by incorporating Cs into the electrodes. Cs gas will be mixed with Ag during DC magnetron sputtering, and the Cs atoms will be introduced inside both the Ti and Ag films. The influence of Cs on both Ti and Ag materials is well understood and the work function has been reduced to 1-1.5 eV [7]. It is an advantage that the fabrication of both electrodes is in situ and the sandwiches are opened in a vacuum, ensuring that the electrode surfaces containing Cs will never be exposed to the atmosphere. Assembly is thereby greatly simplified.

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