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Published in:
Journal of Vacuum Science and Technology. Part B.

DOI:
10.1116/1.2817629

Published: 01/01/2008

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Double oxidation scheme for tunnel junction fabrication

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(Received 10 August 2007; accepted 31 October 2007; published 2 January 2008)

The authors report a method to achieve Al–AlOₓ–Al tunnel junctions with high specific resistance in a controlled manner using a double oxidation technique. The technique is based on the standard method for oxidation repeated on an additional Al layer. The tunnel junctions were characterized with standard methods, such as comparison of room temperature resistance with liquid helium resistance and the authors found them to be of comparable quality to junctions fabricated with standard single oxidation. Fitting with the Simmons model suggests that both the barrier width and barrier height are consistent with those obtained in a single oxidation step. The junction specific capacitance was determined at low temperature to be 68 fF/μm². These junctions, employed in low temperature measurements and applications, demonstrate expected and stable conductance characteristics. The double oxidation method is straightforward to implement in a basic setup for tunnel junction fabrication. © 2008 American Vacuum Society. [DOI: 10.1116/1.2817629]

I. INTRODUCTION

While submicron scale metal-insulator-metal (MIM) tunnel junctions have found much attention and practical applications, there are still unresolved issues with the micron scale junctions as these mature into commercial applications. The most common material for the dielectric layer is thermally oxidized aluminum, AlOₓ. The procedure for producing junctions with this barrier is straightforward: deposit clean Al in a vacuum chamber and flow oxygen into the chamber for a predetermined time at a certain pressure, and cover with a second metal layer. Yet, this standard method for producing tunnel junctions, while straightforward and simple, has a few problems. In particular, it can be difficult to achieve high specific resistance of the tunnel junctions, since the oxide forms a diffusion barrier that shields the underlying metal from further oxidation. Hence, a change of resistance of tunnel junctions over time (i.e., aging effects) has been observed for both large area tunnel junctions and for small ones.

It is believed that the standard process for fabricating AlOₓ produces an oxygen rich compound near to the surface. It relaxes to the stoichiometric stable Al₂O₃ only after some time when oxygen has diffused from the surface into the underlying aluminum, which has been brought forward as a plausible explanation for aging. It was recently reported that annealing of MIM tunnel junctions stabilizes the junctions, lending some support to the idea that aging is related to relaxation of AlOₓ to Al₂O₃. One method to improve the quality of tunnel junctions is to form the dielectric layer in several steps. Obviously, this method has the added advantage of making it possible to fabricate tunnel junctions with high resistance simply by increasing the number of layers. This method has been reported to be in use for magnetic tunnel junction fabrication. In this article, we describe the fabrication of Al–AlOₓ–Al tunnel junctions using a double oxidation method to form a stable dielectric layer. We have investigated the quality of these tunnel junctions using common criteria by determining specific capacitance and resistance, and testing these in low temperature measurements.

II. FABRICATION

In order to increase the tunnel barrier thickness beyond the limits set by the diffusion barrier of the oxide layer, a procedure was developed with the main idea being to evaporate a thin (<1 nm) layer of Al on top of already oxidized Al, whereafter the oxidation procedure was repeated. The second aluminum layer is sufficiently thin such that it oxidizes completely, thereby increasing the thickness of aluminum oxide without leaving layers of Al buried inside the junction.

One application of such junctions is Coulomb blockade thermometry. For this purpose, and in order to facilitate easy characterization of the tunnel junctions, we fabricate junction arrays with seven parallel lines of N=64 junctions in each line in series (see Fig. 1). Each metal island between the junctions has a large cooling fin to guarantee sufficient electron thermalization even at temperatures as low as 50 mK and below. The tunnel junction area is about 2.2 μm². The fabrication method for the test structure is based on the shadow evaporation method pioneered by Dolan. Structures are defined using standard electron beam lithography with a two layer resist scheme. The metals are evaporated with an electron gun source in a vacuum chamber with base pressure of less than 1×10⁻⁷ mbar. The bottom aluminum electrode is evaporated to a thickness of 30 nm at an oblique angle α with respect to perpendicular orientation. The first aluminum layer is oxidized for 10 min at 100 mbar in pure oxygen. After the first evaporation and subsequent oxidation, another aluminum layer with a thickness of 0.6 nm is evaporated and oxidized under the same conditions as the first one. A quartz crystal thickness monitor (Inficon XTC) with a nominal thickness resolution of 0.1 nm is used to observe the evapo-
ration rate. When the rate is stable at 2 Å/s, the shutter is opened for 3 s. The topmost electrode is formed by evaporating aluminum to a thickness of 30 nm at an angle $-\alpha$. The last metal evaporation step is copper to a thickness of 500 nm. With the exception of the thin aluminum layer, deposition rates are kept at 5–10 Å/s.

III. QUALITY CONSIDERATIONS

One measure of the quality of a tunnel junction is the change of its resistance when cooled from room temperature to liquid He temperature. It has been suggested that this is a more reliable criterion for pinhole-free junctions than fitting I-V characteristics of the junction with the standard Simmons model. In practice, approximately 15% increase of junction resistance is reported to indicate high quality Al–AlO$_x$–Al tunnel junctions. Since tunnel junction resistance $R_J$ is inversely proportional to the area $A$ of the junction, the junction specific resistance,

$$R_C = \frac{R_J}{A},$$

is used as a characteristic figure. Fabrication of large area tunnel junctions with a single oxidation step tends to result in limited specific resistance of the tunnel junction. As seen in Table I, even drastic increases in oxide pressure and oxidation time may result in a relatively moderate increase in junction resistance. The introduction of a second oxidation step, as seen in batches 3–5, yields consistently specific resistances that are approximately one order of magnitude higher.

One of the more troublesome characteristics of tunnel junctions is aging, which is generally observed as an increase in resistance over time. Recent studies of aging have mainly concerned small area junctions with one oxidation step. Earlier studies include large area junctions but, again, only for one oxidation step. In order to monitor aging, three samples fabricated with two oxidation steps from the same batch were monitored over a period of over 100 days while stored in ambient air at room temperature; the result is shown in Fig. 2. It is noteworthy that no increase of the resistance was seen, instead for two of the three studied samples the resistance decreased about 5% during the first few days of the measurement. The change of resistance for any of the three samples was well below 10% over this duration indicating that aging was weak for these junctions.

Fitting bias dependence of conductance to the Simmons model is the standard method to determine both the thickness of the dielectric layer and the height of the potential barrier. Voltage dependence of the differential conductance follows:

![Table I](image)

<table>
<thead>
<tr>
<th>Batch</th>
<th>Oxidation pressure (mbar)</th>
<th>Oxidation time (min)</th>
<th>$R_C^{RT}$ (k$\Omega \mu$m$^2$)</th>
<th>$R_C^{He}$ (k$\Omega \mu$m$^2$)</th>
<th>$\Delta R_C / R_C^{RT}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>10</td>
<td>3.24</td>
<td>3.78</td>
<td>17</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>60</td>
<td>6.14</td>
<td>7.60</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>10</td>
<td>37.12</td>
<td>45.22</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>10</td>
<td>33.3</td>
<td>39.82</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>10</td>
<td>58.3</td>
<td>71.5</td>
<td>23</td>
</tr>
</tbody>
</table>

![Fig. 1](image)

(a) Scanning electron micrograph of the structure used to measure tunnel junction characteristics. It is an array of seven parallel lines with 64 tunnel junctions in series in each vertical line. Cooling fins are added to the islands between junctions to facilitate low temperature measurements with minimal decoupling of the electrons to the phonon system. (b) Two tunnel junctions of the array with higher magnification. The junction area is nominally 1.5 $\times$ 1.5 $\mu$m$^2$.

![Fig. 2](image)

Resistances of three arrays with tunnel junctions manufactured with double oxidation. All the three samples were fabricated in the same vacuum cycle in batch 3 (see Table I). The resistance was monitored over an extended time while the junctions were stored in ambient air at room temperature. A small decrease of resistance is seen in the first days but then the junctions stabilize. The overall change in resistance is <10% over this duration.
The capacitance of a tunnel junction is determined from the half width of the feature around zero bias. The capacitance per junction area was found to be about 30–60 fF/µm², often cited experimental values for the specific capacitance of Nb–AlOₓ–Al junctions. Often cited experimental values for the specific capacitance are values for Nb/AlOₓ/Nb junctions which range between 45 and 60 fF/µm². Spectroscopic studies indicate that the oxygen content and distribution depends strongly on the work function of the electrodes. Therefore the capacitance of a tunnel junction with Nb electrodes may not be comparable to that of a junction formed with Al electrodes. Data for thermally oxidized Al–AlOₓ–Al junctions range from slightly below 45 fF/µm² (Refs. 21 and 22) up to 220 fF/µm² (Ref. 23) with many falling in the range between 60 and 110 fF/µm². Our value for specific capacitance is therefore in line with previously measured values for standard Al–AlOₓ–Al junctions.

V. CONCLUSIONS

We have made tunnel junctions using a two step oxidation scheme which utilizes standard procedures for MIM tunnel junction fabrication. This scheme results in tunnel junctions with specific resistances in the 30–60 kΩ·µm² range at room temperature, roughly one order of magnitude larger than the typical resistance with a single oxidation step. The capacitance per junction area was found to be about 70 fF/µm² which is similar to those obtained with a single oxidation step. Using accepted criteria, these junctions are found to be of high quality and exhibit only weak aging.

ACKNOWLEDGMENTS

The authors gratefully acknowledge financial support from Centre for Metrology and Accreditation (MIKES) and valuable discussions with A. M. Savin and R. Blaauwgeers.

1See, e.g., http://www.hypres.com
6J. B. Hansen (private communication).