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Niobium-Silicide Junction Technology for Superconducting Digital Electronics*David OLAYA[†], Paul D. DRESSELHAUS^{†a)}, and Samuel P. BENZ[†], Nonmembers

SUMMARY We present a technology based on Nb/Nb_xSi_{1-x}/Nb junctions, with barriers near the metal-insulator transition, for applications in superconducting electronics (SCE) as an alternative to Nb/AlO_x/Nb tunnel junctions. Josephson junctions with co-sputtered amorphous Nb-Si barriers can be made with a wide variety of electrical properties: critical current density (J_c), capacitance (C), and normal resistance (R_n) can be reliably selected within wide ranges by choosing both the barrier thickness and Nb concentration. Nonhysteretic Nb/Nb_xSi_{1-x}/Nb junctions with $I_c R_n$ products greater than 1 mV, where I_c is the critical current, and J_c values near 100 kA/cm² have been fabricated and are promising for superconductive digital electronics. These barriers have thicknesses of several nanometers; this improves fabrication reproducibility and junction uniformity, both of which are necessary for complex digital circuits. Recent improvements to our deposition system have allowed us to obtain better uniformity across the wafer.

key words: amorphous alloy, Josephson device fabrication, Josephson junctions, superconducting devices

1. Introduction

Digital Superconducting Electronics (SCE), which has the potential for lower power consumption and faster switching speeds compared to some semiconductor technologies, is a promising technology to deliver ultra-high performance computation. The earliest SCE circuits used junctions with lead and lead alloys, but these suffered from poor stability and their properties deteriorated after repeated thermal cycling. Presently, the preferred technology for high-speed superconductive digital circuits, which was developed in the early 1980's, is based on Nb/AlO_x/Nb junctions with barrier thicknesses on the order of 1 nm [1]. These junctions have proved to be stable, reproducible, and able to yield uniform devices.

Important developments have been achieved using this technology; some of the most impressive achievements include a T-flip-flop circuit operating up to 770 GHz [2] and a 4 kbit memory operated at 580 ps and 6.7 mW [3]. For the highest speed and density, circuits rely on high critical current density (J_c) junctions and submicrometer junction dimensions. Tunneling Nb/AlO_x/Nb junctions are hysteretic and need shunting resistors to bring them to the critically damped regime, limiting the circuit density and introducing parasitic inductances. Only very high J_c Nb/AlO_x/Nb

junctions (> 200 kA/cm²) [4] with deep sub-micron dimensions are self-shunted due to their very thin oxide barriers, one or two monolayers thick. Self-shunting in this case is due to metallic micro-shorts across the barrier [5]. For these junctions, J_c uniformity is much more difficult to achieve and may be inherently limited by the random distribution of micro-shorts.

Other attempts have been made to obtain suitable junctions for SCE, with high J_c and no hysteresis, including SINIS [6] and SNIS [7] (S=superconductor, I=insulator, N=normal metal) junction technologies, with Al and AlO_x as normal metals and insulators, respectively. AlN has been evaluated as a barrier material [8] as have SNS junctions with high-resistivity barrier materials such as TiN_x [9], NbN_x [10] and TaN_x [11], for which the resistivity is changed according to the nitrogen concentration and substrate temperature. The only technology that has been partially competitive with Nb/AlO_x/Nb has been NbN-based junctions with various barriers, with the higher transition temperature superconducting NbN, having the advantage of circuit operation near 10 K [12].

We propose an alternative technology for SCE based on Nb/Nb_xSi_{1-x}/Nb junctions. By choosing $x \leq 0.05$, the Nb-Si barriers can be reproducibly tuned between metallic and insulating behavior [13]. A junction with a several-nanometer thick Nb-Si barrier would produce comparable electrical performance to that of high- J_c tunnel junctions, but has the potential for better reproducibility and uniformity.

2. Fabrication of Nb/Nb_xSi_{1-x}/Nb Junctions

NIST has been developing Nb/Nb_xSi_{1-x}/Nb junctions to replace previously successful junction technologies for voltage standards, most notably PdAu and MoSi₂ barrier SNS junctions. Typically, these junctions have a low normal resistance R_n and, as a consequence, low values of $I_c R_n$ (if I_c is to be kept within practical limits). This makes them unsuitable for high-speed electronics. However, unlike tunneling junctions, whose electrical properties are tuned by the oxygen exposure, which defines the barrier thickness, in Nb/Nb_xSi_{1-x}/Nb junctions two controllable parameters, thickness and composition of the barrier, determine the junction's properties [14]. The control of the composition is achieved through the co-sputtering of Nb and Si as shown in Fig. 1.

While the deposition time and rate determine the thick-

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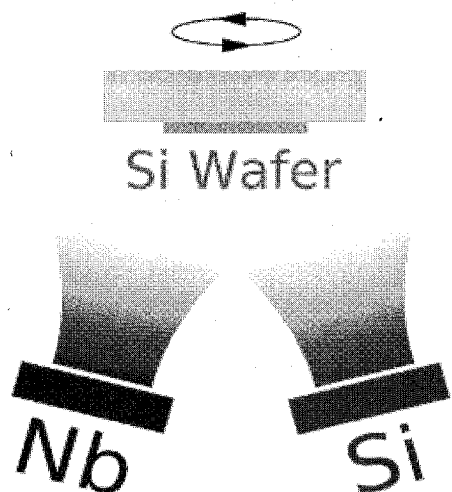


Fig. 1 Cosputtering allows for control of barrier composition as well as thickness, enabling junctions with a wide variety of properties.

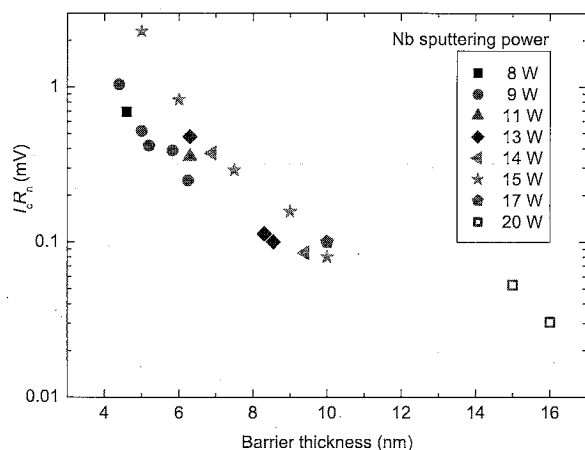


Fig. 2 $I_c R_n$ vs. barrier thickness for Nb/Nb_xSi_{1-x}/Nb junctions with different Nb content in the barrier determined by the power of the Nb sputtering gun. The Si sputtering gun power was set at 200 W for all junctions in the figure.

ness, the composition is determined by the relative powers of the Nb and Si sputtering guns. This allows a continuous spectrum of barrier properties from low resistance, Nb-rich barriers, to insulating barriers of pure silicon. Within a wide range of possible values, J_c and R_n can be reliably and independently selected, giving junctions of varied characteristics. Of particular interest for SCE are junctions with thin barriers in the insulating regime, which have $I_c R_n$ products greater than 1 mV and J_c near 100 kA/cm². Figure 2 shows a variety of $I_c R_n$ values for junctions with different barrier deposition conditions.

In our system, a three-inch diameter silicon wafer substrate with 150 nm of silicon oxide is held against a rotating platen located at approximately 15 cm from the sputtering targets. The platen is cooled with flowing nitrogen gas and a heat sinking film or plate is placed at the back of the wafer against the platen. Patterning of junctions is done by reactive ion etching in a mixture of SF₆ and C₄F₈, giving an

excellent vertical profile and allowing for the fabrication of uniform vertical stacks of junctions [15]. Silicon oxide insulation is deposited by electron cyclotron resonance (ECR) plasma-enhanced chemical vapor deposition, giving a low-stress, high quality oxide. Vias through the oxide are done by reactive ion etching in a mixture of O₂ and CHF₃.

To improve the uniformity of the junctions, an Argon plasma etch is applied to the base electrode and, in the case of vertical stacks, each middle electrode. This process smooths the Nb surface prior to the barrier deposition. In the case of thin barriers, a rough surface would contribute to non-uniformities in J_c . Roughness particularly affects stacks because it accumulates as the stacks are grown vertically [16]. A good etching profile of stacked junctions allows for uniform properties with potential for high-density vertical stacks of junctions for application in output circuits with very small parasitic inductances.

3. Junction Properties

Josephson junctions made with co-sputtered Nb-Si barriers have already been shown to have excellent uniformity and reproducibility in Josephson voltage systems in which tens of thousands of junctions all have sufficiently similar properties to each other in order for 10 V to be obtained from the addition of their first constant voltage step under microwave bias. These junctions are more robust than SINIS (S=superconductor, I=insulator, N=normal metal) junctions that have AlO_x for the insulator, which have also been used in voltage standard applications. SINIS junctions seem to be affected by plasma processing, giving a low yield of working devices [17]. Junctions with Nb-Si barriers, on the other hand, are more robust, due in part to the increased thickness of the barriers, which is of the order of several nanometers. For voltage standards, it has been straightforward to change the characteristic frequency of junctions from 20 GHz to 70 GHz by choosing the appropriate composition and thickness. Excellent uniformity was demonstrated with large circuits of ~70000 nearly identical junctions [17]. Similarly, much faster junctions suitable for SCE with characteristic frequencies above 500 GHz have also been fabricated [18].

An important and desired feature of any junction technology for applications in SCE is the reproducibility of junction properties. For our junctions this can be seen in the dependence of J_c on barrier composition and thickness, as demonstrated in Ref. 16. For a fixed barrier composition, J_c has a nearly exponential dependence on the barrier thickness. This allows us to accurately target the properties of the junctions according to the desired application.

High values of $I_c R_n$ can be achieved with a variety of thickness and composition combinations. More metallic barriers produce large values of J_c , which require smaller lateral fabrication dimensions to maintain practical I_c values. These junctions are ideally suited for SCE logic, because they are intrinsically critically damped, as shown in Fig. 3. Without the need for shunt resistors, they avoid the parasitic inductances arising from shunts and can achieve

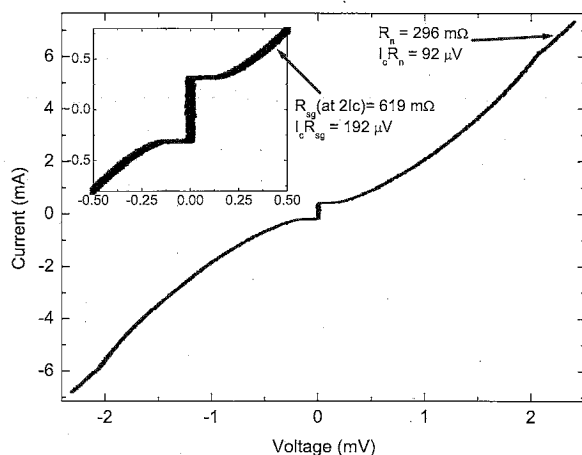


Fig. 3 I - V curve of a single junction with lateral dimensions $2.5 \mu\text{m} \times 2.5 \mu\text{m}$ with 10.8 nm barrier thickness. The deposition powers were 16/200 W for Nb/Si. The inset shows a curve of the same junction limited to low currents.

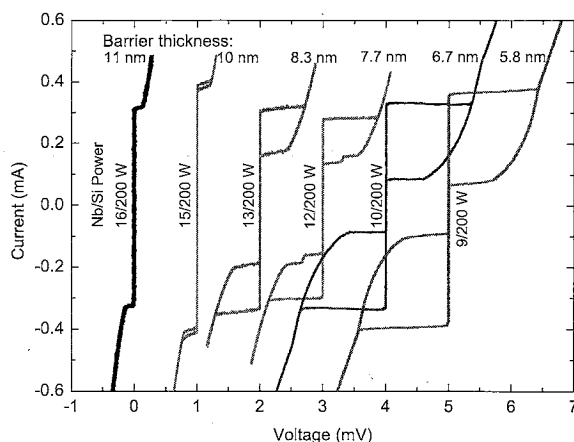


Fig. 4 Current-voltage characteristic for six pairs of junctions designed to have similar J_c but different composition and thickness. Curves are displaced on the voltage axis for clarity. Thinner barriers with lower Nb content display higher characteristic voltage $I_c R_n$ and more hysteresis.

higher circuit density. More resistive barriers will allow larger lateral junction dimensions, but the reduced damping will increase their hysteresis. Hysteretic junctions are suitable for latching logic and output circuits, such as Suzuki stacks [19].

The simultaneous but independent control of composition and thickness allows us to obtain junctions with a chosen J_c but with different resistance and capacitance, so that they have different characteristic frequencies and a different amount of damping, which produces different magnitudes of hysteresis in the current-voltage curves (IVC). As an example, Fig. 4 shows a set of six IVC for pairs of parallel junctions with dimensions of $2.5 \mu\text{m} \times 2.5 \mu\text{m}$. The junction pairs have different composition and thicknesses, but are all designed to have the same value of J_c . As the concentration of Nb decreases, the junctions become more resistive and also more hysteretic, because the less metallic barriers become more resistive. The preferred properties for a specific

Table 1 Growth parameters and properties of Nb/Nb_xSi_{1-x}/Nb junctions.

Power Nb/Si (W)	Thickness (nm)	J_c (kA/cm ²)	C (pF)	I_c/I_{ret}	ϵ
16/200	11	3.9	2.1	1.00	658
15/200	10	4.1	2.1	1.11	593
14/200	9.4	2.9	1.0	1.13	275
13/200	8.3	3.0	1.3	1.86	309
13/200	8.5	2	0.9	1.52	215
12/200	7.7	3.7	1.0	2.04	213
10/200	6.7	2.6	0.6	4.07	121
10/200	6.3	3.9	0.6	4.02	108
9/200	6.3	1.6	0.5	4.45	85
9/200	5.8	3.5	0.6	4.39	91
9/200	5.8	4.1	0.7	4.64	114
9/200	5.8	5.1	0.7	3.75	117
9/200	5.8	6.4	0.6	3.32	100
9/200	5.8	7.4	0.7	2.28	110

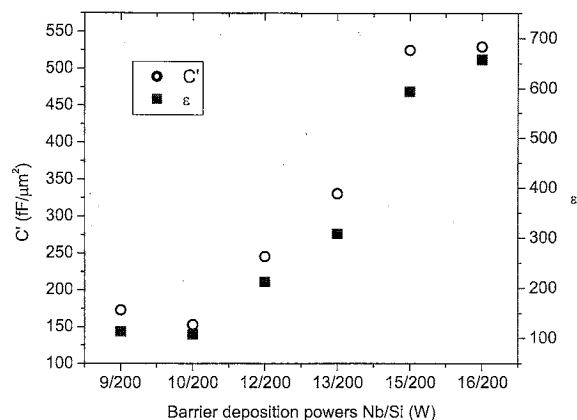


Fig. 5 Specific capacitance, C' and dielectric constant ϵ , of the barrier in Nb/Nb_xSi_{1-x}/Nb junctions. Note that the barrier thickness is decreased together with Nb concentration to maintain J_c constant. This group of junctions is identical to those plotted in Fig. 4.

application can be obtained through the correct choice of thickness and composition. For high-speed digital electronics, for example, high values of $I_c R_n$ can be achieved with a variety of combinations of thickness and composition.

Table 1 shows the growth conditions and measured properties of junctions with different barriers (from different wafers), including J_c , capacitance C , amount of hysteresis (I_c divided by the return current, I_{ret}), and dielectric constant (ϵ) of the barrier. Capacitances were inferred by measuring voltage resonance steps in the IVC of SQUIDS in which flux was coupled by adjusting the current in a directly coupled wire, as described in [20]. The values of C and ϵ decrease as the Nb content of the barrier decreases. Figure 5 shows these trends for the same group of wafers with similar J_c , as in Fig. 4.

In Fig. 3, we can see that the value of the resistance in the sub-gap region (R_{sg}) near to I_c is considerably larger than R_n (the resistance above the superconductor gap voltage). Consequently, $I_c R_{sg}$ is much larger than $I_c R_n$. This value of $I_c R_{sg}$ may be more representative of the speed of

the junction, as it is the value in the region close to the operation point of the junction. Likewise, based on capacitance measurements, for the IVCs in Fig. 4 with little or no hysteresis, the expected value of damping parameter β_c should be around and not much bigger than 1. If we use the values of R_{sg} near I_c and the calculated capacitances from voltage resonance steps, the values for β_c obtained are 1.3 (for 16/200 W) and 2 (for 15/200 W), compared to values a factor of ten smaller when R_n is used. This suggests also that the value of R_{sg} near I_c better represents the junction dynamics and also suggests faster operation than that given by the $I_c R_n$ values in Fig. 2 [21].

4. Improvements in Deposition Conditions

It has been found that junctions having barriers with low Nb content are particularly susceptible to residual impurity gases in the chamber during deposition. Voltage standard circuits operating at 75 GHz were found to have large J_c nonuniformity across the wafer [22]. The origin of the non-uniformity was found to be outgassing from the cooling graphite foil (used to heat-sink the wafer during deposition) and possibly also the platen in back of the wafer. The effect was more pronounced in circuits that were located nearest to the flat of the wafer, where there was a small opening in the wafer holder. A new holder plate with no gap improved the uniformity. Experiments on thicker films made of only the barrier material showed considerable improvement in resistivity uniformity after a new "gapless" holder plate was installed. Before this change, a film deposited with 8/200 W (Nb/Si power) had a mean resistivity of 7.4 m Ω ·cm with a standard deviation of 5.6 m Ω ·cm. After removing the gap and reducing the residual gases, a wafer with similar junction deposition conditions had less than half the average resistivity (3 m Ω ·cm) and more than 10-times lower standard deviation (0.4 m Ω ·cm). A further increase in J_c and decrease of barrier resistivity was obtained by replacing the graphite foil with a solid Al metallic disc for wafer cooling. Unfortunately, it was unclear which residual gas was responsible for the depressed value of J_c . Preliminary studies show that it is also possible that residual water vapor may be responsible for suppression of the critical current density.

As expected, the value of J_c increases either as the Nb content increases or the barrier thickness decreases. J_c also increases when the material impurities in the barrier are reduced. The last five entries of Table 1 show samples with the same composition and thickness; they all have similar values of C and ϵ , but those near the bottom, corresponding to improvements in wafer mounting in the deposition chamber, have higher J_c and, at the same time, less hysteresis. Future work will evaluate the reproducibility of the electrical properties under these deposition conditions.

5. Conclusion

We have shown that the versatility of co-sputtered Nb/Nb_xSi_{1-x}/Nb junctions permits the fabrication of junctions with electrical properties suitable for SCE. Their fabrication is similar to existing technologies, with only the minor modification of cosputtering the barrier. The junctions have been shown to be reproducible and uniform. Work is presently underway on the fabrication and testing of simple digital superconducting circuits based on these junctions.

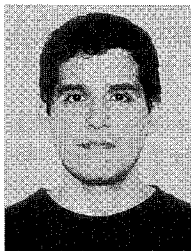
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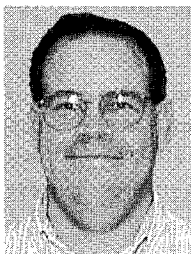
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