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Specific capacitance of $Nb/AlO_x/Nb$ Josephson junctions with critical current densities in the range of 0.1–18 kA/cm^2

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The specific capacitance C_s of $Nb/AlO_x/Nb$ Josephson tunnel junction has been measured by means of the superconducting quantum interference device (SQUID) resonance technique. We have investigated the junctions with critical current densities J_c in the range of 0.1–18 kA/cm^2 and found that $1/C_s$ linearly depends on a logarithm of J_c. This suggests that the barrier thickness is moderately uniform in the junction area and increases continuously during growth. The results also show that increasing J_c reduces time constants of the junction. © *1995 American Institute of Physics.*

The specific capacitance C_s of a Josephson tunnel junction is one of its most important parameters, since many characteristics of Josephson devices are related to C_s of the junction. Its critical current density J_c (or specific-normal-conductance G_n) dependence is especially important because J_c/C_s (or G_n/C_s) determines both the plasma frequency $\omega_p = \sqrt{2\pi J_c/\Phi_0 C_s}$, where Φ_0 is the magnetic flux quantum, and the RC time constant $\tau_{\mathrm{CR}} = C_s/G_n$, which determine the response time of the junction.[1] Because both J_c and C_s are functions of barrier thickness d, C_s is related to J_c. In most applications of Josephson junctions, an appropriate estimate of C_s is required for the design of devices and circuits. Moreover, the relationship between C_s and J_c (or G_n) will give valuable information about the structure of the tunnel barrier.[2] Recently, van der Zant *et al.*[2] have investigated C_s of $Nb/AlO_x/Nb$ junctions for a wide range of J_c, using Fiske mode resonances in one-dimensional arrays of Josephson junctions. They have reported that C_s increases linearly with increasing J_c. In this paper, the results of C_s measurements of $Nb/AlO_x/Nb$ junctions with J_c in the range of 0.1–18 kA/cm^2 will be described. We have used a superconducting quantum interference device (SQUID) resonance technique[3,4] and found that $1/C_s$ linearly depends on $\log J_c$ and $\log G_n$

A method described by Magerlein[4] which utilizes resonance in SQUIDs due to junction capacitance and loop inductance, was used for determining C_s. The inset of Fig. 1 shows the equivalent circuit of the SQUIDs used here. Six symmetric two-junction SQUIDs with different junction sizes and loop inductances were fabricated on each chip in order to obtain various resonant voltages V_r and $\beta_L = 2I_c L/\Phi_0$, where I_c is the critical current of the junction and $2L$ is the loop inductance of the SQUID. The SQUIDs consisted of $Nb/AlO_x/Nb$ trilayers, in which the thicknesses of Nb electrodes and the Al normal layer were 200 nm and less than 6 nm, respectively. An evaporated SiO film (350 nm) was used as an insulating layer for all devices. Additional damping resistance was not used in our SQUIDs. All measurements were performed at 4.2 K.

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In the current-voltage characteristics of symmetric two-junction SQUIDs, a resonant step appears at the voltage,

$$V_r = \Phi_0/2\pi\sqrt{LC_sS}, \tag{1}$$

where S is the area of one junction.[3,4] To determine the C_s, three parameters, resonant voltage V_r, loop inductance $2L$ and junction area S, are necessary. The loop inductance $2L$ was obtained from the modulation period of the critical current by injection of control currents. The error in $2L$ is estimated to be less than ±6%. This error is mainly due to the frequency dependence of the London penetration depth.[5] As Tuckerman and Magerlein[3] mentioned, generally the peak voltage of the resonance step does not agree with the resonant voltage V_r, which was determined by curve fitting to the current-voltage characteristics as described in Refs. 3 and 4. Measured V_r varied from 0.5 to 0.7 mV, which means that resonant frequency was in the range of 240–340 GHz. We estimate the error in V_r to be less than ±8%. We determined the junction area S from the normal conductance of SQUIDs. It is assumed that the specific normal conductance G_n is uniform in a whole wafer region. We have determined G_n by the average of those of 10×10 μm^2 junctions in the same wafer and then estimated S from a ratio of SQUID conduc-

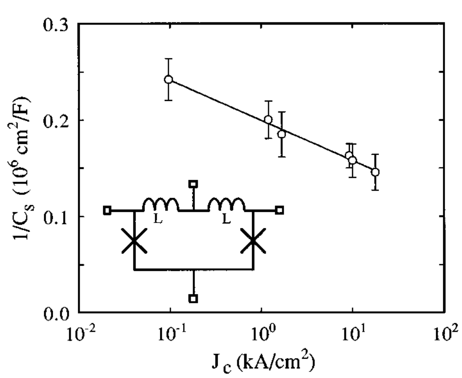

FIG. 1. The relationship between specific capacitance C_s and critical current density J_c. The solid line is a least squares fit, $1/C_s = 0.20 - 0.043 \log_{10} J_c$, where C_s is in $\mu F/cm^2$ and J_c is in kA/cm^2. The inset shows an equivalent circuit of the symmetric two-junction SQUID used here.

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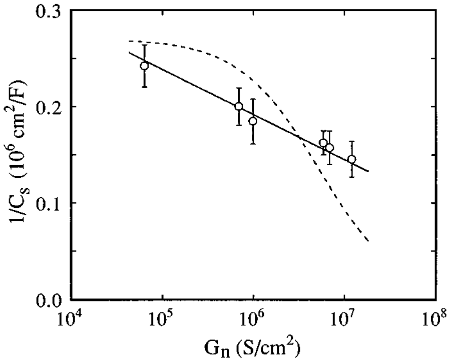

FIG. 2. The relationship between specific capacitance C_s and specific normal conductance G_n. The solid line is a fit using Eqs. (2) and (3) with ϕ=1.5 eV and $\varepsilon_r = 4$. The dashed line, $C_s = 3.7 + 0.70 \times 10^{-6} G_n$, is the dependence reported in Ref. 2.

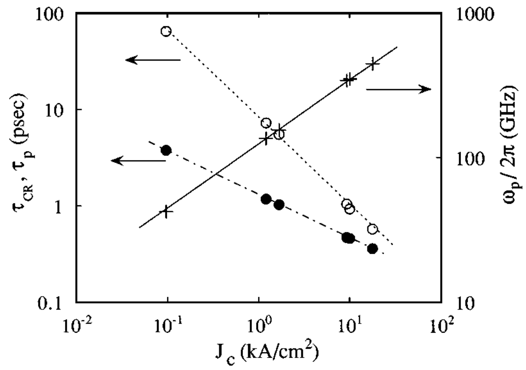

FIG. 3. The plasma frequency ω_p (crosses), the RC time constant τ_{CR} (open circles), and the plasma time constant $\tau_p = 1/\omega_p$ (solid circles) as functions of critical current density J_c.

tance to G_n. Thus, the total error in each measurement of C_s amounted to less than $\pm$22%. Finally, C_s was determined as the average of 3–8 data obtained from one wafer, so the error in C_s is estimated to be $\pm$8% to $\pm$13%.

The stray capacitance is expected to be 5–10 fF depending on the SQUID configuration, assuming that dielectric constant of SiO is 5.7. Because this is much smaller than junction capacitance, we neglect the contribution of the stray capacitance.

We defined J_c as the maximum I_c/S of individual junctions in the same wafer, since the Josephson critical current I_c can easily be reduced by an external noise. J_c is assumed to uniform over a wafer.

The result of the C_s measurements is plotted in Fig. 1. It is found that $1/C_s$ linearly depends on $\log J_c$. This logarithmic relationship is predicted by a simple model in which thickness and barrier height of the insulator are uniform in the junction area and the thickness increases continuously during growth.[2] The solid line in Fig. 1, $1/C_s = 0.20 - 0.043 \log_{10} J_c$, is a least squares fit. Here, C_s is in μF/cm^2 and J_c is in kA/cm^2. For $J_c < 10$ kA/cm^2, the C_s obtained are close to those reported earlier[2,6–8] and consistent with the results of analysis of subgap current-voltage characteristics.[9] However, in the high J_c region, the $J_c = 18$ kA/cm^2 junction showed a smaller C_s than those reported in Ref. 2.

For comparison with theory, the dependence of C_s on G_n is more important than that on J_c, because tunnel theory directly predicts G_n as a function of d. We then obtain J_c from the I_cR_n product. Generally, the I_cR_n product depends on the thickness of the normal layer, the gap of the electrodes, and the transparency of the barrier.[10,11] The result in Fig. 1 is replotted in Fig. 2 as the relationship between $1/C_s$ and G_n. The logarithmic relation is evident. According to tunnel theory,[12] specific tunnel conductance G_n through an insulator with uniform thickness and uniform barrier height is given as

$$G_n = \frac{e^2}{4\pi h d^2}\left(\frac{4\pi d\sqrt{2m\phi}}{h} - 1\right)\exp\left(-\frac{4\pi d\sqrt{2m\phi}}{h}\right), \qquad (2)$$

where ϕ is the barrier height, m is the mass of a free electron, and h is Planck's constant. The specific capacitance is given as a function of d,

$$C_s = \varepsilon_0 \varepsilon_r / d, \qquad (3)$$

where ε_0 is vacuum permittivity and ε_r is relative dielectric constant. Using Eqs. (2) and (3) we calculate the dependence of C_s on G_n with adjustable parameters of ϕ and ε_r. The solid line in Fig. 2 is a fit with ϕ=1.5 eV and $\varepsilon_r = 4$. This is not an exact logarithmic relation but is approximately $1/C_s = 0.47 - 0.047 \log_{10} G_n$, where C_s is in μF/cm^2 and G_n in S/cm^2. The value of ϕ, 1.5 eV, is very close to that reported by Adelerhof *et al.*[13] We do not know the ε_r of aluminum oxide in Nb/AlO_x/Nb junctions. Note that the reported value of ε_r of Al_2O_3 is about 9 at a few hundred GHz,[14] which is larger than the value obtained, $\varepsilon_r = 4$.

The dashed line in Fig. 2, $C_s = 3.7 + 0.70 \times 10^{-6} G_n$, is the experimental result reported by van der Zant *et al.*[2] (we modified their original equation, $C_s = 3.7 + 0.37 J_c$, using their assumption of $I_cR_n = 1.9$ mV). As they described, a linear dependence of C_s on J_c (or G_n) is predicted by a model in which the barrier is assumed to be a mixture of a one monolayer oxide with thickness t_0 and a two monolayer oxide with thickness $2t_0$. Certainly, the assumption that the thickness of the insulator is uniform and increases continuously during growth is somewhat impractical.[2,11] However, the assumption that the barrier consists of only two parts, oxides with thickness of t_0 and $2t_0$ is also an oversimplification. The barrier AlO_x in Nb/AlO_x/Nb junctions is not a single crystal film and a "monolayer" thickness depends on crystal direction. For example, the monolayer thickness of Al_2O_3 varies from 0.41 nm for $(1\bar{1}00)$ to 1.3 nm for (0001). Our experimental result suggests that a continuously variable-thickness model is more suitable for our junctions than a one- and two-monolayers-thickness model, at least for J_c of 0.1–18 kA/cm^2. We cannot explain the cause of the difference between our data and those in Ref. 2, which appear to be within experimental error in the low-J_c region. This is an interesting question and further investigations, including studies on growth mechanism of aluminum oxide,[15,16] are required.

In Fig. 3, ω_p and τ_{CR}, calculated using the measured

J_c, G_n, and C_s, are shown. The plasma time constant $\tau_p = 1/\omega_p$, relating to turn-on delay,[1] is also plotted. It is clearly shown that τ_{CR} and τ_p decrease and ω_p increases monotonically with increasing J_c. In other words, the increase of J_c overcomes the increase of C_s and, consequently, results in the reduction of time constants.

In summary, we have measured C_s of Nb/AlO$_x$/Nb tunnel junctions with J_c ranging from 0.1–18 kA/cm^2 using a SQUID resonance technique and obtained the logarithmic dependence, $1/C_s = 0.20 - 0.043 \log_{10} J_c$ and $1/C_s = 0.47 - 0.047 \log_{10} G_n$. These results suggest that the thickness of the tunnel barrier is moderately uniform and increases continuously during growth. We have obtained a good agreement with conventional tunnel theory, assuming $\phi = 1.5$ eV and $\varepsilon_r = 4$ for the barrier in our Nb/AlO$_x$/Nb junctions. The obtained values of τ_{CR} and τ_p show that increasing J_c improves the response time of the junction.

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