Investigation of Double-Barrier Nb-Al-AlO_x-Al-AlO_x-(Al-)Nb Junctions under High-Frequency Irradiation

Ivan P. Nevirkovets, John B. Ketterson, and Michael Siegel

Abstract—**We have studied experimentally the current-voltage characteristics of double-barrier Nb-Al-AlO$_x$-Al-AlO$_x$-(Al-)Nb junctions exposed to microwave radiation at 4.2 K. Both integer and fractional Shapiro steps were observed. A complicated behavior of the step heights was observed as a function of both the microwave power and an applied magnetic field. Reasonable agreement with the RSJ model was obtained only for the steps 0 to 2 observed in current-voltage characteristics of the junctions with a "clean" middle Al layer. A deviation from RSJ-like behavior was found for higher-order integer steps and fractional steps. Devices with a "dirty" middle Al layer displayed more significant deviation from RSJ-like behavior. Step heights vs. magnetic field dependences in some cases were found to be qualitatively different from the field dependence of the dc Josephson current.**

Index Terms—**Josephson effect, microwave radiation, Shapiro steps, SINIS junctions**

I. INTRODUCTION

RECENTLY, SINIS junctions have attracted much attention as possible candidates to replace externally shunted SIS junctions in superconducting digital circuits [1], [2] (here S, I, and N denote a superconductor, insulator, and normal metal, respectively). In pursuing this goal it is important to gain a deeper understanding of the mechanisms of electrical transport in such junctions. To date, there have been few studies of the behavior of SINIS junctions under microwave radiation [3], [4], and, to our knowledge, there has been no attempt to systematically study the behavior of the Shapiro steps as a function of microwave power and magnetic field and compare it with the theory. Such studies can test which of the existing models, such as Resistively-Shunted Junction (RSJ), Tunnel Junction (TJ), or others, best describes SINIS junctions. This, in turn, is required for describing their behavior as circuit elements. In this work, we present results of an investigation of Nb-Al-AlO$_x$-Al-AlO$_x$-(Al-)Nb junctions under the influence of external microwave radiation. The dependence of the height of Shapiro steps on the microwave power and magnetic field and comparison of the power dependence with the predictions of the RSJ model are reported.

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II. EXPERIMENTAL

The junctions were fabricated using a conventional whole-wafer dc magnetron process for depositing Nb and Al films and optical litography to produce 10 μm × 10 μm two-terminal devices. For the microwave study, two different sets of samples were used. For the junctions of the first type, Nb-Al-AlO$_x$-Al-AlO$_x$-Al-Nb, the thickness of the middle Al film, d_{Al}, was 6 nm; the critical current density, j_c, was 11 A/cm^2. The Al films used for these devices were nominally clean. In the second type junctions, Nb-Al-AlO$_x$-Al-AlO$_x$-Nb, the middle Al film was composed of the two layers with the total nominal thickness d_{Al} = 7 nm. The bottom layer was intentionally contaminated by introducing 1×10^{-5} Torr of oxygen during the dc magnetron sputtering of Al at a total Ar + O_2 pressure of 2 mTorr. The top layer, used to form the barrier, was nominally clean.

The motivation for using "dirty" Al film was to check how its purity affects characteristics of the SINIS junctions. When fabricating the conventional Nb-Al-AlO$_x$-Nb junctions, more attention is usually given to the properties of the Nb as opposed to those of the Al. This may be justified because the characteristics of such "classical" junctions do not crucially depend on the purity of the Al film used to form the tunnel barrier. On the contrary, a variety of current-voltage characteristics (CVC) obtained in different laboratories for SINIS junctions suggests that the properties of these junctions are extremely sensitive to properties of the middle N (Al) layer [5], [6]. Therefore, the dependence of junction properties on the quality of the Al layer is of practical interest to establish a reproducible fabrication technique. Here we used junctions with a "dirty" Al, described in more detail elsewhere [5], [6]. Junctions of this type have a critical current density of 21 A/cm^2.

All the junctions were measured using the four-probe technique in liquid He at 4.2 K. No special circuit was used to match the impedance of the junction to the output circuit of the microwave generator. The power level in dB is given relative to a constant reference power of the generator, but the actual power delivered to the junction is not known.

III. Results and Discussion

A. Current-voltage characteristics

Microwave frequencies in the range of 10 GHz were used. At these frequencies, all the junctions displayed both integer and fractional (at higher irradiation levels) Shapiro steps. The junctions of the first type displayed $n/2$ fractional steps, whereas the junctions of the second type also displayed other subharmonic steps. Fig. 1 shows the CVC of a junction of the first type at different power levels (the solid and dashed curves are for −11.9 dB and −27.9 dB, respectively, and the dotted curve is the unperturbed CVC). The fractional steps typically have a height of the same order as the main integer steps (see the curve corresponding to −11.9 dB; the fractional steps are denoted by arrows). The CVC, perturbed and unperturbed by the microwave field, are rounded by fluctuations and noise. At higher irradiation levels, the CVC displays an asymmetry in the step height (for the steps with the same number $\pm n$) for different directions of the dc bias current.

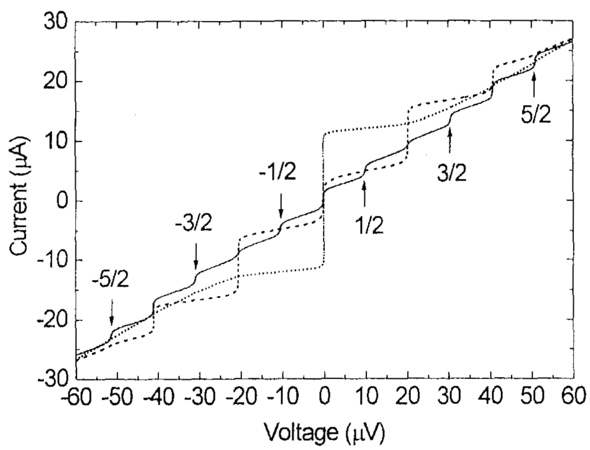

Fig. 1. CVC of a Nb-Al-AlO$_X$-Al-AlO$_X$-Al-Nb junction irradiated at 9898 MHz. Solid and dashed lines correspond to an attenuation of −11.9 dB and −27.9 dB, respectively; the dotted line is the unperturbed CVC.

B. Power dependence

For junctions of the first type, we have simulated the dependence of the integer Shapiro steps within the RSJ model [7], [8] by solving the differential equation for the phase difference numerically [9], [10]. Fig. 2 shows the experimental dependence of the Josephson critical current, I_0, and the Shapiro step heights for n = 1 to 3 as a function of the amplitude of the absorbed microwave current (scatter plot). To obtain the fit shown in Fig. 2 (solid line), we adjusted the critical current to the experimental value, and scaled the microwave current amplitude to the first minimum of the n = 0 step. The reduced frequency, $\Omega = \Phi_0 \nu/(I_c R_N)$, is chosen to approximate the periodicity of the experimental step height with microwave current. Here ν is the frequency of the external microwave radiation, I_c and R_N are the Josephson critical current and normal-state resistance, respectively, and $\Phi_0 = h/2e$ is the flux quantum. The simulation gives optimal results (presented in Fig. 2) for the parameters $\Omega = 0.76$, $\beta_c = 2$ and $\Gamma = 0.013$. The parameter $\Gamma = 2k_B T/(\Phi_0 I_c)$ describes the thermal noise energy in the junction, where k_B is the Boltzmann constant. The Stewart-McCumber parameter, β_c, is given by $\beta_c = 2eI_c R_N^2 C/\hbar$ (here C is capacitance of the junction). One sees a good agreement with the RSJ model for I_0 and the steps n = 1,2. The agreement is not as good for the higher-order steps, $n \geq 3$. Additionally, the fractional steps observed in our experiments have a much higher amplitude than that predicted by the RSJ model, and we could not obtain a reasonable fit to the power dependence using this model.

The junctions of the second type display an even more complicated behavior of the Shapiro steps. Fig. 3 shows the dependence of the 0th step (the dc Josephson branch) and the

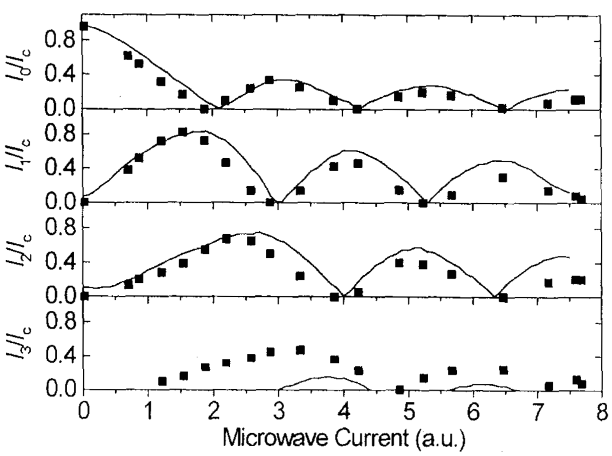

Fig. 2. Dependence of the Josephson critical current, I_0, and Shapiro steps n=1 to 3 as a function of the amplitude of the 9898 MHz microwave current for a Nb-Al-AlO$_X$-Al-AlO$_X$-Al-Nb junction of the first type.

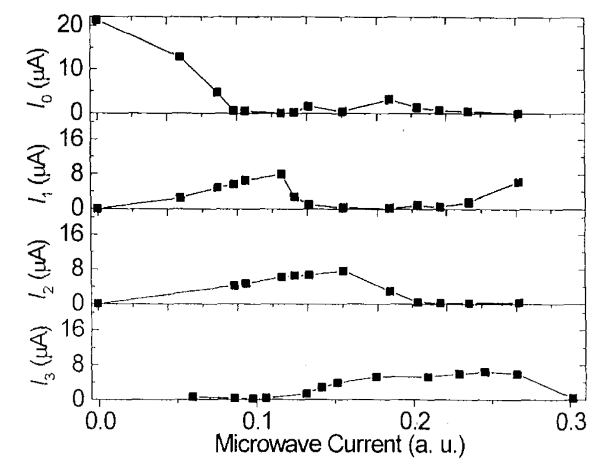

Fig. 3. Dependence of the Josephson critical current, I_0, and Shapiro steps n = 1 to 3 as a function of the amplitude of the 10050 MHz microwave current for a Nb-Al-AlO$_x$-Al-AlO$_x$-Nb junction of the second type.

steps 1 to 3 on the amplitude of the microwave current applied to the junction with a "dirty" Al middle film. This dependence qualitatively differs from that expected from the RSJ model for reasonable values of the junction parameters. Also, the fractional steps (showing $^1/_2$, but also higher-order subharmonics) cannot be treated within the RSJ model.

C. Magnetic field dependence

Since the height of the Shapiro steps is proportional to the magnitude of the zero-voltage Josephson critical current, this, in principle, can be used to test the current-phase, $I(\varphi)$, dependence at a finite voltage, if the junction is biased at a step. The form of the $I_n(H)$ dependence (where I_n is the current amplitude of the nth Shapiro step and H is an applied parallel magnetic field) is expected to be the same as that for the $I_0(H)$ dependence. Deviations from this form may occur if the function $I(\varphi)$ does not coincide with that at $V = 0$.

To record the $I_n(H)$ dependence, we adjusted the microwave power to have the maximum step height at $H = 0$. We have found that the $I_n(H)$ dependences for most of the measured Shapiro steps are proportional to $[\sin(\pi\Phi/\Phi_0)]/(\pi\Phi/\Phi_0)$, and therefore, the relation $I = I_0\sin\varphi$ probably holds at finite voltage (here Φ is the magnetic flux penetrating the junction). However, in some cases pronounced deviations were observed. A typical case recorded for the $n = {}^1/_2$ step obtained for a junction of the second type at 9472 MHz and an attenuation of −4.3 dB is shown in Fig. 4. It was observed that the anomalous $I_n(H)$ dependence is characteristic of strongly asymmetric steps with respect to the CVC where the Shapiro steps are suppressed by a magnetic field, as is shown in the inset of Fig. 4. Here, the $n = {}^1/_2$ step (curve 1) is plotted together with the CVC measured under the same conditions but in an applied magnetic field of 100 G, which suppresses the step completely (curve 2). One can see that the top and bottom parts of the step have a different height. The height of these parts as a function of H was separately recorded using a voltage criteria of 0.3 μV (the voltage interval −0.3 μV to +0.3 μV around the crossing point is marked by vertical strokes).

In Fig. 4, curves 1 and 2 show the field dependences of the top and bottom parts of the $n = {}^1/_2$ step, respectively. Curve 1 closely follows the form $A[\sin(\pi\Phi/\Phi_0)]/(\pi\Phi/\Phi_0)$, where A = const; however, curve 2 has a quite different behavior. The total dependence of the step can be obtained by summing the two dependences, if the current for the two parts is calculated from the crossing point (see the plot in the inset). As a result of such a summation, we obtain the curve 3, which has a minimum at $H = 0$.

Similar $I_n(H)$ dependences are observed also for integer Shapiro steps.

In some cases we clearly observed a period of the $I_n(H)$ diffraction pattern that was half that of the $I_0(H)$ dependence for the same junction, as is seen from a comparison of the respective dependences in Fig. 5 and Fig. 6. Fig. 5 shows the upper part of the step $n = {}^1/_2$ at 10050 MHz and −10.6 dB attenuation; experimental dependence $I_0(H)$ is shown in Fig. 6 (solid line).

It should be noted that the zero-voltage Josephson current of all our junctions can be reasonably well fitted by the form $I_0[\sin(\pi\Phi/\Phi_0)]/(\pi\Phi/\Phi_0)$ at 4.2 K (dotted line in Fig. 6). Therefore we suggest that deviations from the $I = I_0\sin\varphi$ dependence, if any, can be significant only at finite voltage.

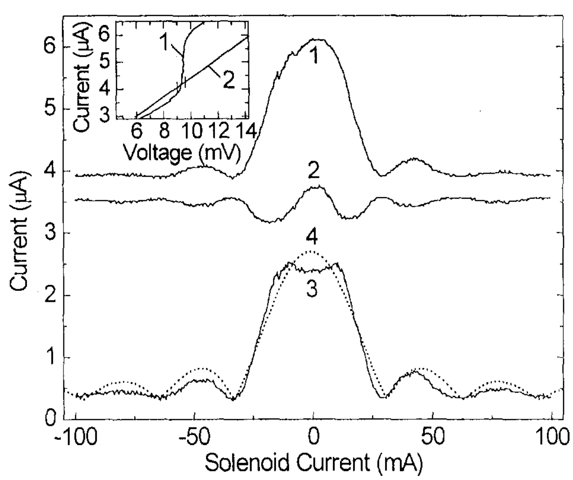

Fig. 4. $I_n(H)$ dependence for the step $n = {}^1/_2$ obtained for a junction of the second type at 9472 MHz and an attenuation of −4.3 dB. Curves 1 to 3 are the magnetic field dependences of: the top portion, the bottom portion, and the whole step, respectively. The form of the dependence proportional to $[\sin(\pi\Phi/\Phi_0)]/(\pi\Phi/\Phi_0)$ is shown by the dotted curve 4. Inset shows the CVC in the vicinity of the step $n = {}^1/_2$ in zero applied magnetic field (curve 1) and in the field of 100 G (curve 2).

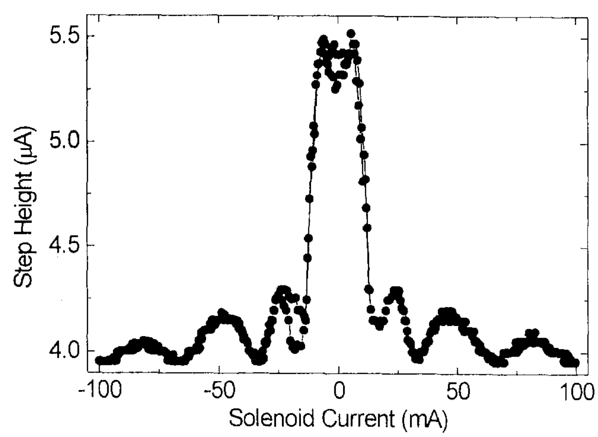

Fig. 5. Height of the upper part of the Shapiro step $n = {}^1/_2$ as a function of solenoid current for a junction of the second type at 4.2 K. The microwave frequency was 10050 MHz, and the attenuation was −10.6 dB.

D. Discussion

Both the power and magnetic field dependences of the height of the Shapiro steps displayed deviations from the behavior expected from the RSJ model. Although the origin of the deviations is not well understood, we suggest the following reasons. First, due to the tunneling nature, the

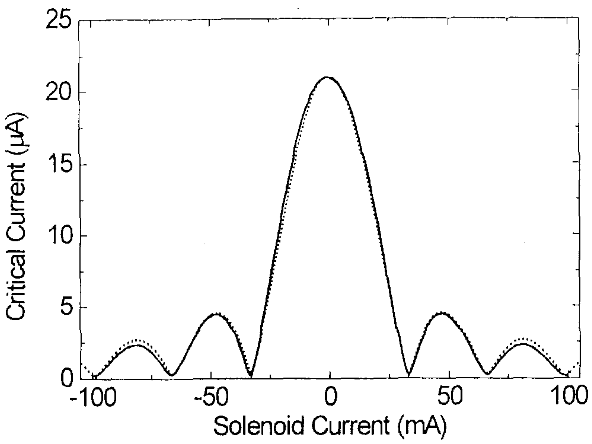

Fig. 6. $I_0(H)$ dependence for the same junction (cf. Fig. 5) at 4.2 K. The dependence $I_0[\sin(\pi\Phi/\Phi_0)]/(\pi\Phi/\Phi_0)$ is shown by the dotted curve.

conductivity of the SINIS junctions is nonlinear. In spite of internal shunting, the non-linearity is present even at low voltages. At higher voltages, where deviations from the RSJ model are pronounced, the effect of nonequilibrium quasiparticles in the Al interlayer also has to be considered.

Second, the deviations may be related to the nature of electron transport intrinsic to double-barrier SINIS junctions with a thin N layer. Specifically, the coherent tunneling effects found in such devices at finite voltage [6] may result in a current-phase relation that deviates from an $I_c\sin\varphi$ dependence. Apparently, our experimental data on the magnetic field dependence of the step height suggest that a non-sinusoidal current-phase relation may take place at finite voltage. These coherent effects can be stronger in the junctions with a "dirty" Al interlayer due to the following reasons: (1) higher transparency of the tunnel barriers; (2) an enhanced superconducting transition temperature of the "dirty" Al film; (3) increased probability of Andreev reflection due to confinement of quasiparticles near the SIN (NIS) interfaces [11], [12]. This might cause more complicated behavior of such junctions in a microwave field as compared with the behavior of conventional devices with "clean" Al.

IV. Conclusion

We have investigated Shapiro steps for two types of Nb-Al-AlO_x-Al-AlO_x-(Al-)Nb junctions at various power levels of external microwave radiation and in an applied magnetic field. Both integer and fractional steps are observed. For the junctions with a "pure" middle Al layer, the power dependence of the low-order ($n = 0$ to 2) steps can be reasonably well fitted by the RSJ model. For the junctions with a "dirty" Al layer, even for the low-order steps, we could not obtain satisfactory agreement of the experimentally observed behavior with the RSJ model. Also, the height of the fractional steps is not in agreement with predictions of the RSJ model. In addition, a peculiar behavior of the steps on the applied constant magnetic field is found. It may be due to deviations from an $I_c\sin\varphi$ dependence for the Josephson current, taking place at finite voltage, although the diffraction pattern at zero voltage can well be fitted using the sinusoidal dependence.

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