The specific capacitance of Nb/Al-AlOₓ/Nb SIS junctions with extremely low RₙA product

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Abstract—This paper provides new insight regarding the specific capacitance of Nb/Al-AlOₓ/Nb SIS junctions with low RₙA product. Employing the direct junction capacitance measurement method, the specific capacitance (Cₛ) and RₙA of several junctions with various RₙA values ranging from 8.8 to 68 Ω·µm² was studied. We noticed non-negligible scatter in the measured RₙC (normal resistance times junction capacitance) product for the junctions with the same RₙA value. We demonstrated that the local variations in the thickness distribution of the tunnel barrier could have resulted in the scatter of the RₙC data. We also show that, even at such low microwave frequencies as in our direct measurement method, the previously neglected nonlinear susceptance should be accounted, especially for junctions with low RₙA values. We present the measured Cₛ vs RₙA data for Nb/Al-AlOₓ/Nb junctions.

INTRODUCTION

The ever growing need for having wider RF and IF bandwidth in radio astronomical receiver sets stringent requirements on the SIS junction properties such as having extremely low RₙA (< 20 Ω·µm²) values and submicron area of the device. The junction capacitance affects both the RF and IF bandwidth of SIS mixers and plays a crucial role in designing tuning circuitry [1]. At low RₙA values, the accurate value of the junction capacitance cannot be ascertained mainly due to the disagreement among the previous indirect measurements of the specific capacitance (Cₛ) reported in the literature [2]–[4]. In order to achieve improved accuracy compared with the previous methods, we presented a direct microwave measurement method employing a dedicated cryogenic calibration technique [5]. Our method with uncertainties down to ±2%, has an advantage over the previously used approaches, which for instance, involved extraction of the SIS junction capacitance from model of a complex superconducting resonant structure.

In this paper, great care was taken to extract the true geometrical junction capacitance. It was found that even at such low frequencies (f=4 GHz), the susceptance [6], [7] obtained by the Kramers-Kronig transformation of the imaginary part of the response function (i.e. quasiparticle dc IV characteristics), should be calculated and subtracted from the measured capacitance. Interestingly, we found that this susceptance, which hereafter will be referred to as the nonlinear susceptance, is significant for junctions with low RₙA values. Additionally, the scatter in Cₛ resulted from the effect of local non-uniformities in the tunnel barrier [8] should also be considered while determining the junction capacitance. Employing the direct method in this study and extracting the true geometrical specific capacitance, the Cₛ vs RₙA data is obtained.

EXPERIMENT AND RESULTS

We fabricated 34 Nb/Al-AlOₓ/Nb SIS junctions with RₙA and junctions’ nominal areas range of 8.8–68 Ω·µm² and 3.6–20 µm², respectively. The details of the trilayer deposition parameters and the junction fabrication process are available in [5], [9]. The range of AlOₓ oxygen exposure parameter for these junctions was 1530–13000 Pa.s, which is presented in details for each batch of junctions in our recent publication [8]. In order to obtain the RₙA value, the true junction size (A) (which accounted for the dimension variation due to the fabrication process) was estimated and the junction normal resistance Rₙ was extracted as explained in [5], [8]. The complex impedance of these junctions were directly measured at 4 GHz center frequency and at 4 K temperature. The calibration at 4 K was performed using the time-domain processing techniques and the gap voltage biased junction as the short-circuit reference [5], [10]. Then an Agilent ADS equivalent circuit model [5] was used in which the model parameters were adjusted based on the calibration. Later the SIS junction capacitance was extracted once the best fit was achieved between the model and the experimental data. More details on this procedure can be found in [5].

The measured junction capacitances (Cₘ) for the batch with RₙA=9.4 Ω·µm² are presented in Figure 1 and Figure 2. In this study, we calculated the contribution of the reactive component of the tunneling current, which results from the extreme nonlinearity of this dc I-V relation at the gap voltage [6], [7]. The resulted nonlinear susceptance calculated through the Kramers-Kronig transform of the dc I-V curve [6], [7] was capacitive under our measurement conditions [11] and was non-negligible even at such low operating frequencies (e.g. Cₙ in Figure 1). As can be seen in Figure 1, at low RₙA values, Cₙ is comparable to the Cₘ. More details regarding the nonlinear capacitance calculation and its important contribution can be found in [6], [7], [11]–[13]. It should be noted that the nonlinear capacitance was found to be more significant for junctions with low RₙA values [11]. Also, for junctions with the same RₙA, Cₙ
was higher for those with lower $R_n$ (see Figure 1). The true geometrical capacitance ($C_g$ in Figure 1) was then obtained by subtracting the $C_n$ from $C_m$. The measured and the true geometrical junction capacitances as a function of the estimated junction area ($A$) are presented in Figure 2. The specific junction capacitance is the slope of the fitted lines to the $C$ ($A$) data points. As can be seen, the true geometrical junction capacitance results in a lower junction specific capacitance.

In [8], we investigated the origin of the scatter of the area-independent $R_n C_g$ product (see Figure 3). We found that the scatter of as much as 40% could not only be attributed to the area estimation and the measurement uncertainty of the $R_n C_g$, which varies depending on the junction area and is between just ±2% to ±11.2% for the largest and smallest junctions among all the batches, respectively. Employing an illustrative model [8] and the obtained local thickness distribution of the AlO$_x$ tunnel barrier in Nb/Al-AlO$_x$-Nb trilayer (using high resolution transmission electron microscopy) we demonstrated that these variations in the thickness distribution of the tunnel barrier result in the scatter of the $R_n C_g$ data, which is consistent with our measurements. It should be noted that the scatter of the $R_n$ translates into the scatter in both specific capacitance and $R_n A$. The “local” nature of such variations over the wafer area states that averaging out the effect of these non-uniformities in junction parameters, $R_n C$, specific capacitance, and $R_n A$ is less probable at the junction size scaled down. Also, such variations could be different depending on the trilayer deposition system, and hence resulting in different reports of the specific capacitance for the same $R_n A$ [11].
The data of the measured \((C_{ms})\) and the true geometrical specific capacitance \((C_{gs})\) as a function of the \(R_nA\) value for each batch is illustrated in Figure 4. The obtained \(C_{gs} (R_nA)\) data is compared with the previously reported experimentally obtained relations in [11]. Reference [11], also proposes an improved and more accurate model for the \(C_n(R_nA)\) relation, which can greatly improve the performance of SIS mixers.

**Conclusions**

In this paper, the results of the directly measured junction capacitance of 34 Nb/Al-AlOx/Nb SIS junctions with various oxygen exposure parameters were considered. It was shown that the nonlinear capacitance obtained from the Kramers-Kronig transform of the dc I-V curve is significant for junctions with low \(R_nA\) even at frequencies of a few GHz. The resulting \(C_{gs} (R_nA)\) relation was presented. Our findings show that for junctions with low \(R_nA\) values and submicron area, the scatter of \(C_n\) as a result of local thickness non-uniformities becomes more significant and should be considered.

**References**


