On Specific Capacitance of SIS Junctions

Parisa Yadranjee Aghdam*, Hawal Marouf Rashid, Alexey Pavolotsky, Vincent Desmaris, Denis Meledin and Victor Belitsky

Chalmers University of Technology, Gothenburg, Sweden

*Contact: parisa.aghdam@chalmers.se, phone +46-31-772 1838

Abstract—**We have discussed possible reasons of scatter in the specific capacitance measurement results reported by different authors. This observed scatter of the measurement data at higher critical current densities (lower R_nA values) could be due variation of the tunnel barrier thickness within the same junction realized in various laboratories. We have shown this through modelling of the tunnel barrier as discrete areas of n, n-1 and n+1 monolayers. This results in a spread of the SIS junction specific capacitance for the same current density. Also, the reported data difference could be a consequence of the high uncertainty of the measurement methods. We developed and demonstrated a measurement method proved to provide a high accuracy in characterization of SIS junction capacitance. At the conference, we will present modelling and the data for direct measurement of SIS junction specific capacitance and compare these data with the earlier reported measurements.**

Superconductor-Insulator-Superconductor (SIS) mixers have been a workhorse in radio astronomy receivers for the last few decades. SIS mixers with Nb/Al-AlO_x/Nb trilayer are commonly recognized for their lowest-noise performance at operating frequencies up to 1 THz [1]–[3].

The SIS junction is produced by means of thin film technology and topologically resembling a parallel-plate capacitor. The performance of the SIS mixer is largely dependent and limited by its intrinsic capacitance. To design accurate RF tuning circuits and thus obtaining optimum sensitivity, the junction capacitance needs to be accurately known.

The limitation of these junctions is at high current densities (J_c>20 KA/cm^2 or R_nA<10 Ω.cm^2) that is accompanied by higher subgap (leakage) current. The increased subgap current is a result of emergence of areas across the barrier with sufficiently high transmittance where multiple Andreev reflections may contribute to this extra current [4],[5]. Therefore, at low R_nA, increased leakage current indicates a more pronounced impact of barrier nonuniformity on junction characteristics. This thickness distribution is also directly observed through advanced microscopy techniques; see for example [6]. In [6], it is concluded that in thin barrier junctions, it is only a small percentage of the junction area (<10 %), which contributes to the most of electron tunnelling current across the barrier. This is a consequence of the exponential dependence of the tunnelling current on the barrier thickness where the nonuniformities create active regions which contribute the most to the tunnelling current.

It is natural to represent the barrier thickness as a discrete variable corresponding to the integer number of oxide monolayers. At very high current densities, the thickness reaches down to few monolayers [4]. The barrier thickness nonuniformity directly affects the junction intrinsic capacitance. Since the details of the barrier thickness distribution, as well as its dielectric permittivity, are generally unknown, the junction capacitance needs to be measured accurately.

In Fig. 1, we summarized the data experimentally obtained for measured specific capacitance (C_s) as a function of R_nA. These measurements were performed using various methods for the SIS junctions produced in different laboratories. As an example, van der Zant et al. [7] measured the capacitance of one-dimensional parallel Josephson junction array using Fiske steps method and has shown that over the range of measurements (R_nA>10 Ω.μm^2 and Jc < 20 kA/cm^2), C_s changes linearly with J_c, C_s=0.0037J_c+37 (C_s in fF/μm^2 and J_c in A/cm^2). Fig. 1 presents this linear relation assuming $J_c=\pi V_g/4(R_nA)$. Van der Zant et al. pointed out that the extrapolation of the linear fit beyond the measurement range becomes erroneous at R_nA<10 Ω.μm^2. Lea et al.[8] also used the Fiske steps method to measure a wide range of specific capacitances which resulted in an exponential fit C_s=49.0exp(0.0002J_c) (C_s in fF/μm^2 and J_c in A/cm^2). This exponential fit significantly deviates from the rest of the rest of the measurements, see dashed line in Fig. 1.

Maezawa et al. [9] measured the specific capacitance of Josephson junctions by means of SQUID resonance method. The authors fitted the measurement results by assuming uniform barrier height and uniform thickness, which yielded C_s=1/(0.47-0.047log(1/ R_nA)) (C_s in μF/cm^2 and R_nA in Ω.cm^2), c.f. Fig.1. It can be observed that the results from Maezawa et al. and van der Zant et al. are very close; however, diverging when reaching R_nA<20 Ω.μm^2 .

Fig. 1 clearly shows that the specific capacitance data measured by different authors significantly scatters. Noticeably, the difference in the measured specific capacitance increases when approaching higher current densities/barrier transparencies. Inspired by [4],[7], we suggest that it is the barrier thickness nonuniformity, which is responsible for the scattering of the specific capacitance measured by different authors.

Apart from the barrier thickness nonuniformity, the methods used for the SIS junction capacitance measurements themselves have high uncertainty. This is mainly due to assumptions made in the employed models regarding the material parameters, e.g., London penetration depth in Nb films, the relative permittivity of the sputtered dielectric film and its thickness. In order to uniquely define the specific capacitance, specifically at low R_nA values, accurate and direct characterization of the junctions is required.

We have developed a method for the direct measurement of the SIS junction capacitance [10]. In this method the one-port S-parameter of the junctions are measured at cryogenic temperatures over IF frequencies of 2-6 GHz. The calibration is performed by using the junction biased at the gap voltage which represents a short-circuit reference. In order to see the effect of the capacitance, the junction is biased at the subgap voltage where the differential resistance is the highest. The time-gated S11 of the junction biased at the gap and the subgap is recorded. Then an equivalent circuit-model representing the two measurements is set to extract the junction capacitance. In these measurements, the absolute uncertainty is reported to vary between 5-6.8% amongst different junction areas.

Fig. 1 shows the data points (diamonds) for the junctions of different areas obtain by our direct capacitance measurement method [10]. Fig. 2 shows the measured SIS junction capacitance versus junction area. The fitted line slope in this figure gives the specific capacitance of the junctions.

Worth mentioning, our specific capacitance measurement points and the data point from [11] reasonably follow the relation C_s=0.3/ln(R_nA) where C_s is in pF/μm^2 and R_nA in Ω.cm^2 [12].

The observed spread of the C_s data especially at the low R_nA end can be illustrated by modelling the barrier thickness as discrete number of n, n-1 and n+1 monolayers of the barrier oxide, $n=d/d_0$; d is the barrier thickness and d_0 is the monolayer . The R_n, R_{n-1} and R_{n+1} are calculated for the fractions A_n, A_{n-1} and A_{n+1} of barrier area. The R_n is calculated using the tunnelling theory [13] with assumption of uniform barrier height and uniform barrier thickness for each given A_n. The total R is calculated as a parallel connection of resistance from areas with different barrier thicknesses with their corresponding R_n, $R_{n-1,}$ and $R_{n+1.}$ For the modelling the initial value of barrier height was set to 2 eV for the 1.35 nm barrier thickness [14]. The relative permittivity of the oxide layer is chosen to ε_r=8 for the calculation of the specific capacitance [15]. We could easily observe that the very similar resistances of the barrier could be realized by the different combinations of A_n, A_{n-1} and A_{n+1}, resulting; however, in the noticeably different capacitance values (circles with illustrated n number of monolayers at Fig.1). At high R_nA end this difference was minor, however, at the lower R_nA end, the difference was quite noticeable, partly explaining the differences in $C_s(R_nA)$ relations obtained by the different authors.

At the conference, we will present the method and results of the direct measurements of the SIS junction specific capacitance for the lower end of the R_nA range.

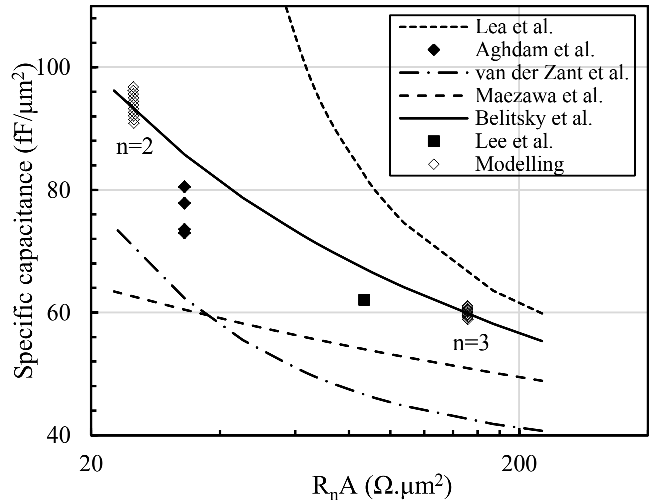

Fig. 1. The comparison of the available specific capacitance data of the Nb/Al-AlO$_x$/Nb SIS tunnel junction as a function of R_nA value. The lines show the reported fitted curves obtained from experimental data amongst various laboratories. The filled diamonds are experimental points from our direct capacitance measurement method for R_nA=33.1 Ω.μm^2. One data point (square) from Lee et al. is also presented. The modeling result (empty diamonds) is also presented for the (n) number of monolayers thickness.

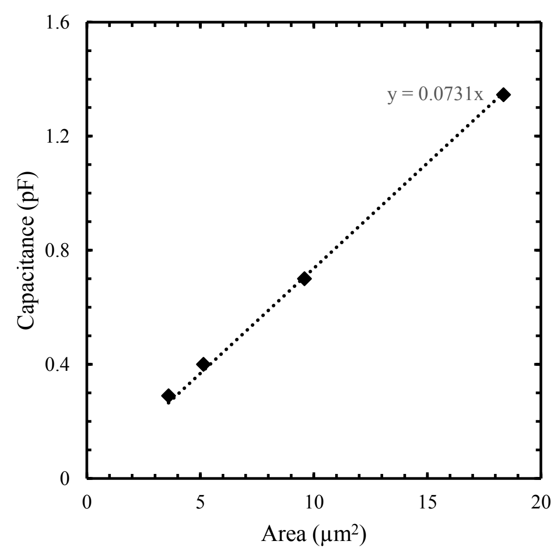

Fig. 2. The measured capacitance values for SIS junction with four different areas using [10]. The linear trendline shows the specific capacitance of 73.1 fF/μm^2.

Summarizing, in this paper, we discuss possible reasons for the observed differences in the measured specific capacitance C_s for the SIS junctions of the same R_nA for Nb/Al-AlO$_x$/Nb superconducting tunnel junctions. We suggest the observed scatter is due to the difference in the barrier thickness and its distribution across the junction area realized in the different labs. We illustrate the suggested mechanism with a model assuming the tunnel barrier as a composition of monolayers. Finally, we present the direct measurement of the SIS specific capacitance and compare the result with the earlier reported numbers.

REFERENCES

[1] J. Tucker and M. Feldman, "Quantum detection at millimeter wavelengths," *Rev. Mod. Phys.*, vol. 57, no. 4, pp. 1055–1113, Oct. 1985.

[2] B. Billade, O. Nystrom, D. Meledin, E. Sundin, I. Lapkin, M. Fredrixon, V. Desmaris, H. Rashid, M. Strandberg, S.-E. Ferm, A. Pavolotsky, and V. Belitsky, "Performance of the First ALMA Band 5 Production Cartridge," *IEEE Trans. Terahertz Sci. Technol.*, vol. 2, no. 2, pp. 208–214, Mar. 2012.

[3] V. Belitsky, I. Lapkin, V. Vassilev, R. Monje, A. Pavolotsky, D. Meledin, D. Henke, O. Nystrom, V. Desmaris, C. Risacher, M. Svensson, M. Olberg, E. Sundin, M. Fredrixon, D. Dochev, S.-E. Ferm, and H. Olofsson, "Facility heterodyne receiver for the Atacama Pathfinder Experiment Telescope." pp. 326–328, 2007.

[4] A. W. Kleinsasser, F. M. Rammo, and M. Bhushan, "Degradation of superconducting tunnel junction characteristics with increasing barrier transparency," *Appl. Phys. Lett.*, vol. 62, no. 9, p. 1017, Mar. 1993.

[5] T. Greibe, M. P. V. Stenberg, C. M. Wilson, T. Bauch, V. S. Shumeiko, and P. Delsing, "Are 'Pinholes' the Cause of Excess Current in Superconducting Tunnel Junctions? A Study of Andreev Current in Highly Resistive Junctions," *Phys. Rev. Lett.*, vol. 106, no. 9, p. 097001, Feb. 2011.

[6] L. J. Zeng, S. Nik, T. Greibe, C. M. Wilson, P. Delsing, and E. Olsson, "Direct observation of the thickness distribution of ultra thin AlOx barrier in Al/AlOx/Al Josephson junctions," *arXiv Prepr. arXiv1407.0173*, 2014.

[7] H. S. J. van der Zant, R. a. M. Receveur, T. P. Orlando, and a. W. Kleinsasser, "One-dimensional parallel Josephson-junction arrays as a tool for diagnostics," *Appl. Phys. Lett.*, vol. 65, no. 16, p. 2102, 1994.

[8] D. M. J. Lea, "Integrated test structures for characterization of thin films for superconductor-insulator-superconductor devices and circuits," Univ. Virginia, 1996.

[9] M. Maezawa, M. Aoyagi, H. Nakagawa, I. Kurosawa, and S. Takada, "Specific capacitance of Nb/AlOx/Nb Josephson junctions with critical current densities in the range of 0.1–18 kA/cm2," *Appl. Phys. Lett.*, vol. 66, no. 16, p. 2134, 1995.

[10] P. Yadranjee Aghdam, H. Rashid, A. Pavolotsky, V. Desmaris, D. Meledin, and V. Belitsky, "Direct Measurement of Superconducting Tunnel Junction Capacitance," *Submitt. to IEEE Trans. Terahertz Sci. Technol.*, 2014.

[11] G. S. Lee and A. T. Barfknecht, "Geometric and material dispersion in Josephson transmission lines," *IEEE Trans. Appiled Supercond.*, vol. 2, no. 2, pp. 67–73, Jun. 1992.

[12] V. Belitsky, S. W. Jacobsson, S. A. Kovtonjuk, E. L. Koliberg, and A. B. Ermakov, "100 GHz Mixer with Vertically Integrated (stacked) SIS Junction Array," *Int. J. Infrared Millimeter Waves*, vol. 14, no. 5, pp. 949–957, 1993.

[13] J. G. Simmons, "Generalized Formula for the Electric Tunnel Effect between Similar Electrodes Separated by a Thin Insulating Film," *J. Appl. Phys.*, vol. 34, no. 6, p. 1793, 1963.

[14] J. Rowell, M. Gurvitch, and J. Geerk, "Modification of tunneling barriers on Nb by a few monolayers of Al," *Phys. Rev. B*, vol. 24, no. 4, pp. 2278–2281, Aug. 1981.

[15] M. Gurvitch, "High quality refractory Josephson tunnel junctions utilizing thin aluminum layers," *Appl. Phys. Lett.*, vol. 42, no. 5, p. 472, Mar. 1983.