Electrodynamics of highly spin-polarized tunnel Josephson junctions

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The continuous development of superconducting electronics is encouraging several studies on hybrid Josephson junctions (JJs) based on superconductor/ferromagnet/superconductor (SFS) heterostructures, as either spintronic devices or switchable elements in quantum and classical circuits. Recent experimental evidence of macroscopic quantum tunneling and of an incomplete 0–π transition in tunnel-ferromagnetic spin-filter JJs could enhance the capabilities of SFS JJs also as active elements. Here, we provide a self-consistent electrodynamical characterization of NbN/GdN/NbN spin-filter JJs as a function of the barrier thickness, disentangling the high-frequency dissipation effects due to the environment from the intrinsic low-frequency dissipation processes. The fitting of the I–V characteristics at 4.2 K and at 300 mK by using the Tunnel Junction Microscopic model allows us to determine the subgap resistance $R_{\text{sg}}$, the quality factor $Q$ and the junction capacitance $C$. These results provide the scaling behavior of the electrodynamical parameters as a function of the barrier thickness, which represents a fundamental step for the feasibility of tunnel-ferromagnetic JJs as active elements in classical and quantum circuits, and are of general interest for tunnel junctions other than conventional SIS JJs.

I. INTRODUCTION

Ferromagnetic Josephson junctions (SFS JJs) have attracted considerable attention in the emerging fields of superconducting spintronics [1–5] and as quantum and classical devices, since they have been proposed as energy-efficient memories [6–9] and as passive π shifters (phase inverters) in quantum circuits [10–12]. However, in standard metallic SFS JJs, the $I_cR_N$ product is of the order of a few microvolts or less [2, 3, 11]. $I_c$ and $R_N$ being, respectively, the critical current and the normal state resistance. All these JJs are overdamped and thus characterized by high quasiparticle dissipation [11, 13, 14]. This has hampered the use of ferromagnetic JJs as active switching elements in different classical and quantum circuits, since for such applications it is important to have a rather high $I_cR_N$ product and low damping [13]. Low-dissipative ferromagnetic junctions use an additional insulating layer between one of the superconducting electrodes and the ferromagnetic barrier (SIFS JJs) [7, 15–17] or a ferromagnetic insulator barrier (SI/S JJs) [18–22] and may present key advantages for some applications, thus increasing the overall impact of JJs based on ferromagnetic barriers [7, 16, 17, 23, 24].

Heterostructures incorporating ferromagnetic insulator tunnel barriers have been theoretically proposed as quantum devices such as quiet ferromagnetic flux-qubits, based on anomalous 0–π transitions [19–21], and as classical devices for digital electronics [18] and efficient electron refrigeration [25]. Among the ferromagnetic insulators, GdN has been used in superconducting spin valves [26], switchable JJs based on the interfacial exchange field [27], and in spin-filter NbN/GdN/NbN JJs, which represent the first SI/S JJs. Some of their properties have been studied in Refs. [28–32]. The first evidence of macroscopic quantum tunneling (MQT) in ferromagnetic JJs is an indication that spin-filter JJs can be used as active quantum devices [31]. These JJs are characterized by a thickness-dependent spin polarization because of the splitting in the GdN insulator band structure induced by its magnetic exchange energy [28]. This property, together with the nontrivial magnetic structure of the barrier, causes an incomplete 0–π transition for the spin-filter efficiency ($P$) above 90%. Such an incomplete 0–π transition could be related to the presence of spin-triplet correlations, with implications for the 0–π technology [32].

This work aims at providing a self-consistent determination of the electrodynamic parameters in highly spin-polarized NbN/GdN/NbN junctions [Fig. 1 (a)]. For conventional JJs in the underdamped regime and with large $I_c$, measurements of Fiske steps have been successfully used to derive the capacitance $C$, while the amplitude of the hysteresis in the $I–V$ curve allows us to estimate the quality factor $Q$ within the resistively and capacitively shunted junction (RCSJ) model [33, 34]. However, when the junctions fall in the moderately damped regime or are characterized by low values of $I_c$ (or critical current density $J_c = I_c/A$, where $A$ is the cross section), it is more complicated to isolate the effective capacitance and the intrinsic dissipation sources of the junction from contributions due to the environment and the external circuit. Thus, more sophisticated methods are required for the analysis of the dissipation [33, 35–38]. We use the conventional tunnel junction microscopic (TJM) model to obtain a self-consistent estimation of $C$, $Q$, and the resistance associated with the quasiparticle dynamics $R_{\text{sg}}$, which are es-
Figure 1: In (a): sketch of spin-filter JJs. The area of the devices is $7 \times 7 \, \mu\text{m}^2$ (dashed blue window). In (b): washboard potential of a Josephson junction. The brown double arrow represents the oscillating motion at the plasma frequency of the phase particle in the superconducting state. In this regime, the damping is determined by the high-frequency quality factor $Q_1$. The dashed green line represents the steady motion of the particle that rolls down the washboard in the voltage state. In this regime, the damping is determined by the low-frequency quality factor $Q_0$.

II. METHODS

Dissipation in a JJ is frequency dependent and the quality factor is given by $Q(\omega) = \omega_p R(\omega) C$, where $\omega_p = (2eI_c/(\hbar C))^{1/2}$ is the plasma frequency \cite{33, 34}. In terms of the phase dynamics in the tilted washboard potential \cite{33}, the phase particle in the supercurrent branch oscillates in one well of the potential at the plasma frequency $\omega_p$, while the voltage state involves steady motion of the phase particle ($\omega \sim 0$) \cite{38}. High-frequency ($\omega \sim \omega_p$) dissipation at the switching from the superconducting to the resistive state (see the brown double arrow in Fig. 1 (b)) is determined by the high-frequency damping $Q_1$ and is mainly affected by the environment, i.e., the circuit in which the junction is embedded \cite{35–38}. Low-frequency dissipation in the subgap branch of the $I-V$ curves ($\omega \sim 0$) (see the green dashed arrow in Fig. 1 (b)) and the corresponding low-frequency damping $Q_0$ are affected by the intrinsic tunnel resistance, which is set by the subgap resistance $R_{sg}$ \cite{37, 38, 41–43} as

$$Q_0 = \omega_p CR_{sg}. \quad (1)$$

The TJM model provides a complete microscopic description of a JJ, using the tunneling-Hamiltonian formalism \cite{33, 34}, and it is commonly employed for modeling superconducting quantum-interference devices (SQUIDs) and rapid-single-flux-quantum (RSFQ) logic gates and circuits \cite{44–47}. This model can describe the subgap branch and the low-frequency electrodynamics of any JJ that shows tunneling conduction, without taking into account the exact expression for the current-phase relation (CPR), which could be nontrivial in the case of unconventional JJs such as the spin-filter JJs analyzed in this work \cite{30}. Therefore, it provides a powerful tool to investigate and determine $Q_0$ in junctions far from the underdamped regime and it enables us to isolate the dissipative components coming from the environment. It is particularly relevant since quasiparticle tunneling is a figure of merit in all classical and quantum circuits and has been, in general, a limit for standard SFS JJs. Measurements down to 300 mK of the $I-V$ characteristics are performed by using an evaporation cryostat, while measurements down to 20 mK are performed in a wet dilution refrigerator. Customized RC, copper powder filters, and room-temperature electromagnetic interference (EMI) filters guarantee high precision and resolution in the microvolt and nanoampere range. More details on the measurement setup can be found in Refs. \cite{31, 48}, while information regarding the fabrication processes is given in Refs. \cite{28, 30, 49}. We measure the $I-V$ curves of junctions with different GdN thickness $t$ at 20 mK, 300 mK, and 4.2 K by current biasing the samples with a triangular waveform at 11.123 Hz and by measuring the voltage across the junction. We extract $I_c$ at a voltage value far from the noise detected in the supercurrent branch. The normal resistance $R_N$ is calculated with a linear fit above $V_g = (\Delta_1 + \Delta_2) / e = 3.50 \, \text{mV}$, with $\Delta_1$ and $\Delta_2$ being the gap energies of the two superconducting NbN electrodes.

TJM simulations are calculated by using pscan2 \cite{50}, a Python module optimized to simulate SFQ logic-based superconducting circuits that typically work at 4.2 K. One
of the subroutines of this software allows to simulate the $I-V$ characteristic of a JJ in electronic circuits with different degrees of complexity \cite{1}. The PSCAN2 subroutine calculates time-averaged voltages $V$ across the device as a function of a bias current $I$. $L_c$, the Stewart-McCumber parameter $\beta = Q_0^2$, the gap voltage $V_g$, the ratio $L_RN/V_g$, and the ratio $R_N/R_{sg}$, $R_{sg}$ being the resistance of the subgap branch, are the software parameters that govern the shape of the $I-V$ curves. $I_c$ and $V_g$ measured directly from the $I-V$ curves in our experimental setup are affected by errors of 1% and 2%, respectively, while $R_N$ is obtained by fitting the ohmic region of the $I-V$ curves and is affected by an error of 3%. Since these values can be obtained with high precision, they can be set as fixed parameters, as well as the ratio $L_{RN}/V_g$. $\beta$ and the ratio $R_N/R_{sg}$ are the fitting parameters. The Stewart-McCumber parameter modifies the amplitude of the hysteresis in the $I-V$ curve, without affecting the subgap region \cite{2}. The ratio $R_{sg}/R_{sg}$, instead, modifies both the subgap shape and the hysteresis amplitude \cite{2}.

In our simulations, we reproduce the current biasing of a JJ with a current generator in series with the filtered lines of our experimental setup (approximately 200 $\Omega$). For each spin-filter JJ with a certain GdN thickness $t$, we choose the best-fit parameters $Q_0$ and $R_{sg}$ in such a way that the deviations from the experimental curves are minimal. The errors on $Q_0$ and $R_{sg}$ represent the range of values that provide a significant overlap between the experimental $I-V$ characteristics and the simulated curves within the TJM model and are of 6% and 10% respectively.

The GdN thicknesses in the junctions analyzed in this work range from 2.5 to 4.0nm, while $P$ ranges from 88% to 98%, respectively (Tab. II), falling in the highly spin-polarized regime. In the special case of spin-polarized systems, $R_N$ has to be redefined as the combination of the two resistances associated with the presence of different tunnel conductances for spin-up and spin-down electrons, because of the spin-filtering effect (see the Appendix). The subgap shape in the $I-V$ curves is linked to the quasiparticle dynamics in the junction. The quasiparticle current in a spin-polarized system has been expressed theoretically and analytically in the case of symmetric spin-filter JJs by taking into account the magnetic nature of the tunnel barrier and the spin-filtering effect \cite{51}. Simple calculations allow us to verify that the quasiparticle current in these devices has the same expression both in the case of conventional tunnel JJs, i.e., for $P = 0$ and a magnetic exchange field in the tunnel barrier $h = 0$, and in the ideal and extreme situation of perfect spin polarization ($P = 100\%$) (see the Appendix). The conventional TJM model does not take into account the magnetic exchange field of the I$_f$ barrier in spin-filter junctions, which can be important in the intermediate regime between these two extreme cases.

The systematic fitting of the $I-V$ curves at 4.2 K as a function of the barrier thickness confirms that the shape of the $I-V$ curves is mostly determined by the standard parameters of the junction ($C$, $R_{sg}$, $Q_0$). Further consistency is given by the $I-V$ fitting through the frequency dependent RCSJ model for the junction with the highest $P$, as shown in section III. Below 4.2 K, NbN/GdN/NbN JJs with $P$ up to 98% show an incipient 0-\pi transition in the $I_c(T)$ curves, which can be understood in terms of spin-triplet correlations arising because of the presence of both the spin-filtering effect and a nonuniform magnetic activity in the I$_f$ barrier \cite{32}. Therefore, deviations between the experimental curves and simulations at 300 mK can be due to the magnetic nature of the barrier, which the TJM model does not take into account. However, the estimated fitting parameters give an upper bound to $Q_0$ and $R_{sg}$, and a term of comparison for possible applications of spin filter JJs at very low temperatures, as discussed in section IV.

\section{RESULTS}

As one can observe in Fig. 3, the critical current density $J_c(t)$, with cross section $A = 49 \mu$m$^2$, and the $R_NA(t)$ curves at 300 mK obey to a typical tunnel behavior, thus confirming the insulating nature of the ballistic GdN barrier \cite{32}. $R_NA(t)$ exhibits the characteristic exponential thickness dependence:

\begin{equation}
R_NA(t) = \frac{2tA}{3\sqrt{4m_eE}} (h/e)^2 e^{\frac{2}{\pi} \sqrt{4m_eE}},
\end{equation}

where $m_e$ is the free electron mass, $e$ is the electron charge and $E$ is the mean energy-barrier height seen by the charge carriers \cite{52}. In Tab. I, we report $I_cR_N$ at 4.2 K, at 300 mK, and at 20 mK, measured from the $I-V$ curves. The characteristic voltage $I_cR_N$ decreases by increasing the barrier thickness, as well as the corresponding Josephson frequency $\omega_c = I_cR_N2e/h$. At 4.2 K, it ranges from 80 GHz for the thinnest junction to 1 GHz for the thickest one. At lower temperatures, we measure higher values of the $I_cR_N$ product. These values are higher than those usually achieved for SFS JJs and comparable to those of some SIFS heterostructures \cite{1, 3, 7, 11, 15, 16}. For barrier thicknesses lower than...
The decrease of factor $Q$ is the subgap resistance [41–43]. The low-frequency quality factors $Q$ are particularly relevant for low values of the subgap resistance. The errors on the characteristic voltage are given by a propagation of maximum errors on $I_c$ (1%) and $R_N$ (3%).

Table I: Parameters of the measured spin-filter junctions: thickness $t$, spin-filtering efficiency $P$, characteristic voltage $I_c R_N$ at 4.2 K, 300mK and 20mK. The errors on the characteristic voltage are given by a propagation of maximum errors on $I_c$ (1%) and $R_N$ (3%).

| $t$ (nm) | $P$ (%) | $I_c R_N$@4.2 K ($\mu$V) | $I_c R_N$@300mK ($\mu$V) | $I_c R_N$@20mK ($\mu$V) |
|----------|---------|----------------------|---------------------|---------------------|
| 2.5      | 88      | $136 \pm 3$          | $179 \pm 4$         | -                   |
| 3.0      | 93      | $24.2 \pm 0.5$       | $38.3 \pm 0.8$      | $44.0 \pm 0.9$      |
| 3.5      | 96      | $9.9 \pm 0.2$        | $19.0 \pm 0.4$      | -                   |
| 4.0      | 98      | $2.8 \pm 0.1$        | $5.1 \pm 0.2$       | $6.1 \pm 0.2$       |

In Fig. 3, we present the $R_N A(t)$ product measured at 300mK (black circles) as a function of the barrier thickness along with a fit using Eq. 2 (dashed curve). In red, critical current density $J_c(t)$ measured at 300mK as a function of the GdN thickness $t$ (diamonds) along with an exponential fit (full line). The error bars are of the order of 1% on measured values for $I_c$, and of 3% for $R_N$.

2.5 nm, the characteristic voltage is as high as a few millivolts [28, 31, 32].

In Fig. 4, we present the $I−V$ curves measured at 4.2 K (black points) and TJM simulations (red straight lines) obtained by using pscan2 software. We collect in Tab. II the fitting parameters $R_{sg}$ and $Q_0$. The thicker the barrier is, the higher is the subgap resistance [41–43]. The low-frequency quality factor $Q_0$ decreases with the thickness. This is due to both the decrease of $I_c$ and of $C$ of the barrier with the thickness [33].

The increase in the $Q_0$ factor for increasing $t$ indicates a smooth transition from an underdamped regime ($Q_0 \sim 10$) to a moderately damped regime with phase diffusion (PD) ($Q_0 \sim 1$) [38, 53, 54]. The presence of the PD regime is confirmed by the finite slope in the supercurrent branch for the junction with a 4.0 nm-thick barrier [38], which pscan2 simulations cannot reproduce, since they do not take PD processes into account. Monte Carlo simulations can reproduce the finite slope in the supercurrent branch, taking into account multiple escape and retrapping processes in the phase dynamics, which are particularly relevant for low values of the $Q_1$ factor and $E_j$ comparable with the thermal energy $k_B T$, as in the case of the spin-filter junction with a 4.0 nm-thick barrier [38]. In Fig. 4 (d), a Monte Carlo fit according to the frequency dependent RCSJ model is shown (blue square points), in the case of the spin-filter junction with a 4.0 nm-thick barrier [38]. In Fig. 4 (d), a Monte Carlo fit according to the frequency dependent RCSJ model is shown (blue square points), with high-frequency $Q_1 = 0.13$ and low-frequency $Q_0 = 2.8$. This is consistent with the outcomes based on the TJM model.

The environment plays an important role in determining the value of $Q_1$. The ratio between the low- and high-frequency quality factors $Q_1/Q_0$ equals the ratio between the resistance of the environment $R_{env}$ and the subgap resistance, $R_{sg}/R_{env}$, since $Q_0$ is written in terms of the quasiparticle dissipation (Eq. 1), while $Q_1$ can be expressed in terms of the environment resistance $R_{env}$ [36–38]. For the junction with a GdN barrier thickness of 4.0 nm, $R_{env}$ is approximately 150$\Omega$, which is of the same order of magnitude of the resistance of the lines in our experimental setup.

Our analysis allows us to estimate the capacitance $C$ of the barrier and its dependence on the barrier thickness, using Eq. 1 (see Tab. II). The value of $C$ for the thinnest GdN barrier is consistent with a previous estimation based on SCDs measurements [31]. In Fig. 5, we plot the junction capaci-
The red line in Fig. 5 is the function calculated with Eq. 1.

The red line in Fig. 5, follows the expected behavior for tunnel JJs [56].

The red line in Fig. 5 (black circles), along with TJM model simulation by using PSCAN software (red straight line) for the spin-filter JJ with $t = 4.0 \, \text{nm}$. Quality factor $Q_0$ and subgap resistance $R_{sg}$, estimated from the simulations are collected in Tab. II. In b): incipient 0-π transition in the $I_c(T)$ for the spin-filter JJ with $t = 4.0 \, \text{nm}$, as reported in Ref. [32].

Table II: Parameters of the measured spin-filter junctions: thickness $t$, subgap resistance $R_{sg}$, quality factor $Q_0$ and capacitance $C$ calculated with Eq. 1. $R_{sg}$ and $Q_0$ have been determined by fitting the $I - V$ curves according to the TJM model. The errors on the subgap resistance and the quality factor are of the order of 10% and 6%, respectively, while the error on the capacitance (20%) is obtained by propagation of the errors on $Q_0$ and $R_{sg}$, and are of the same order of magnitudes of those in Ref. [36].

| $t$ (nm) | $R_{sg}@4.2 \, \text{K}$ (Ω) | $R_{sg}@300 \, \text{mK}$ (Ω) | $Q_0@4.2 \, \text{K}$ | $Q_0@300 \, \text{mK}$ | $C$ (pF) |
|---------|-----------------|-----------------|-----------------|-----------------|-------------|
| 2.5     | 59              | 93              | 16              | 48              | 1.6 ± 0.3   |
| 3.0     | 82              | 350             | 7.3             | 35              | 1.1 ± 0.2   |
| 3.5     | 440             | 1700            | 6.6             | 32              | 0.26 ± 0.05 |
| 4.0     | 3000            | 13000           | 2.6             | 26              | 0.018 ± 0.003 |

Figure 5: In black: capacitance values of spin-filter JJs as a function of the GdN barrier thickness $t$ (black circles), along with parallel-plate capacitance $C(t)$ fit (dashed curve). In red: specific capacitance $C_s$ of the analyzed junctions as a function of $R_NA$ (red diamonds) along with a tunnel barrier model fit (straight line, see Eq. 3). The error bars on $C$ and $C_s$ are calculated using the propagation of the errors on $R_{sg}$, $Q_0$ and $I_c$.

The red line in Fig. 5 is the function

$$ R_NA(C_s) = \frac{2\hbar e \varepsilon_r}{3C_s \sqrt{4m_e E}} (\hbar/e)^2 e^{\frac{2q_0 e t}{\hbar \varepsilon_r}} \sqrt{4m_e E}, \quad (3) $$

which is obtained by replacing $t$ in equation 2 with its dependence on the specific capacitance $C_s$, $t = \varepsilon_0 \varepsilon_r / C_s$.

In Fig. 6 (a) we show the $I - V$ characteristic measured at 300mK (black points) and TJM simulations (red straight lines) for the junction with a 4.0nm-thick barrier, which corresponds to the highest spin-filtering efficiency analyzed in this work. $Q_0$ and $R_{sg}$ for all the devices are collected in Tab. II. The best-fit curve at 300mK is characterized by a smaller $R_{sg}$ compared to the experimental one. We can attribute this deviation to the unconventional magnetic activity discussed in Ref. [32], which is at a maximum in the case of most spin-polarized JJs, where the magnetic nature of the barriers manifests in a steep increase of $I_c(T)$ below 2K [Fig. 6 (b)] [32].

The conventional TJM model does not take the magnetic activity in the $I_f$ barrier into account, nor the spin-dependent tunneling mechanism and the unconventional thermal behavior of $I_c$, thus giving a systematic underestimation of $R_{sg}$, as shown in Fig. 6 (a). However, despite the presence of these deviations, $R_{sg}$ estimated for all the junctions increases when decreasing the temperature $T$ due to the tunnel nature of the conduction mechanisms in the system [42] and $Q_0$ increases because of the increase of $R_{sg}$, as expected.

In Fig. 7, we finally present a comparison between the normalized $I - V$ curves measured at 4.2K and 300mK and the...
and 29nA for b). The critical current at 300mK is 4nA for a) and 26nA for b). The current is normalized to the switching value $I_s$, while the voltage is normalized to the critical current $I_c$, by comparing the subgap branches of the $I-V$ curves. $I_c$ at 20mK are 4.75µA for a) and 29nA for b). The critical current at 300mK is 4.64µA for a) and 26.7nA for b). The amplitude of the hysteresis in the $I-V$ curves increases when going toward lower temperatures, pointing to an increase of $Q_0$ and also as a consequence of $R_{sg}$.

IV. DISCUSSIONS AND CONCLUDING REMARKS

The use of the TJM model on parent compounds allows to achieve a consistent and robust picture of tunnel-ferromagnetic JJs with a quantitative insight on key electrodynamic parameters, such as $Q_0$, $R_{sg}$ and $C$.

The estimated $Q_0$ values at 4.2K are up to two orders of magnitude higher compared to those of standard SFS heterostructures that typically operate in the overdamped regime like SNS JJs, with $\beta$ ranging from $10^{-3}$ to $10^{-1}$ [33, 34, 57]. $Q_0$ values are of the same order of magnitude of conventional SIS junctions commonly used to drive and for the read-out of components in quantum and classical circuits [58, 59]. Moreover, the $Q_0$ values increase up to one order of magnitude for the 4.0nm thick barrier, when lowering $T$ to 300mK. This sets a lower limit that can only increase at lower temperatures (see Fig. 7), and suggests possible implementation of spin-filter JJs in low-dissipative $\pi$-qubits. $\pi$-superconducting RF-SQUIDS with ferromagnetic-insulating barriers were only theoretically suggested as quiet qubits efficiently decoupled from the fluctuations of an external magnetic field [20, 21]. A spin-filter JJ with $t = 3.0$nm and an $A \sim 50$µm$^2$ has an estimated charging energy $E_c \sim 900$µK, and a Josephson energy at 20mK $E_J \sim 100$K, which means $E_J/E_c \sim 10^5$, suitable for a flux-qubit [39, 40].

In the frame of the 0-$\pi$ technology, spin filter JJs analyzed in this work can be implemented also as complementary $\pi$-junctions for phase-bias of conventional flux-qubits (passive elements) in which the high values of the subgap resistance $R_{sg}$ could increase the dephasing time of the overall circuit [13]. The dephasing time is proportional to $E_{J}^2 R_{sg}$ of the $\pi$-junction [13]. The subgap resistance in this work ranges from tens of ohms to some kilo-ohms at 4.2K, but when decreasing $T$, $R_{sg}$ increases from a factor 2 to 5 increasing $t$ at 300mK. The dephasing time of a circuit with a spin-filter JJ with $t = 3.0$nm thick barrier can be comparable with that of circuits with SIFS $\pi$-junctions [15], and can increase of at least a factor 100 compared to circuits with standard metallic $\pi$ shifters [12, 59]. In standard metallic SJS JJs typical resistances are at most $\sim 1$Ω, while $R_{sg}$ for the junction with a 3.0nm thick barrier at dilution temperature is at least 350Ω.

The subgap resistance is crucial for the engineering of transmon qubits. As suggested in Ref. [60], in these circuits quasiparticle tunneling can affect the relaxation and coherence times [60]. The values obtained in this work can be promising even for potential application of tunnel-ferromagnetic JJs in transmon qubits. The order of magnitude of the ratio $E_J/E_c$ for the investigated junctions scales with the thickness from $10^0$ to 10. Adapting the area of the devices to conventional dimensions in transmon qubits ($A \sim 1$µm$^2$), lower values of $E_J/E_c$ can be achieved, falling in the typical range of transmon qubit [39, 40, 61]. As an example, reducing the cross section to $A \sim 1$µm$^2$, $E_J$ of the spin-filter JJ with $t = 3.5$nm becomes $\sim 280$mK, while $E_c$ becomes $\sim 180$mK, so that $E_J/E_c \sim 2$. Moreover, reducing the junction area by a factor $\sim 50$, $R_{sg}$ should increase up to values of the order of $50 - 100$kΩ, thus further reducing quasiparticle noise. The same arguments are valid for the junction with $t = 4.0$nm GdN barrier, which is characterized by a subgap resistance $\sim 10$ times higher.

In conclusion, this work represents the first electrodynamic characterization of spin-filter JJs, and a fundamental step to use these devices as active elements in superconducting circuits. Our comparative and self-consistent approach allows to obtain the scaling-law as a function of the barrier thickness of fundamental electrodynamic parameters, such as $C_s(t)$, $R_{sg}(t)$ and $Q_0(t)$, providing the possibility to engineer spin-filter JJs as a function of the junction area in order to meet specific circuit requirements. Even if the ferromagnetic JJs analyzed in this work are not ideal SIS JJs, we succeeded in the determination of these fundamental electrodynamic parameters at 4.2K by using a conventional TJM model, and we provided a lower bound for $R_{sg}$ and $Q_0$ at 300mK. The underestimation of $R_{sg}(t)$ observed at 300mK is due to the absence of the spin-filtering effect and of the magnetic activity of the barrier in the TJM model. Further studies are needed to implement a microscopic modelization of peculiar properties of the JJ barrier, such as spin-selective tunneling mechanisms and triplet correlations.

The same approach can be successfully extended to different types of tunnel junctions other than conventional SIS JJs.
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[1] F. S. Bergeret, A. F. Volkov, and K. B. Efetov, “Odd triplet superconductivity and related phenomena in superconductor-ferromagnet structures,” Rev. Mod. Phys. 77, 1321–1373 (2005).

[2] J. W. A. Robinson, J. D. S. Witt, and M. G. Blamire, “Controlled injection of spin-triplet supercurrents into a strong ferromagnet,” Science 329, 59–61 (2010), http://science.sciencemag.org/content/329/5987/59.full.pdf.

[3] Trupti S. Khaire, Mazin A. Khasawneh, W. P. Pratt, and Norman O. Birge, “Observation of spin-triplet superconductivity in Co-Based Josephson Junctions,” Phys. Rev. Lett. 104, 137002 (2010).

[4] Matthias Eschrig, “Spin-polarized supercurrents for spintronics,” Physics Today, 43 (2011).

[5] J. Linder and Jason W. A. Robinson, “Superconducting spintronics,” Nature Physics 11, 307–315 (2015).

[6] V. V. Ryazanov, V. A. Oboznov, Yu. Rusanov, A. V. Veretenikov, A. A. Golubov, and J. Aarts, “Coupling of two superconductors through a ferromagnet: Evidence for a π junction,” Phys. Rev. Lett. 86, 2427–2430 (2001).

[7] T.I. Larkin, V. V. Bol’ginov, V. S. Stolyarov, V. V. Ryazanov, I. V. Vernik, S. K. Tolpygo, and O. A. Mukhanov, “Ferromagnetic Josephson switching device with high characteristic voltage,” Applied Physics Letters 100, 222601 (2012).

[8] E. Goldobin, H. Sickinger, M. Weides, N. Ruppelt, H. Kohlstedt, R. Kleinert, and D. Koelle, “Memory cell based on a φ Josephson junction,” Applied Physics Letters 102, 242602 (2013), https://doi.org/10.1063/1.4817152.

[9] Bethany M. Niedzielski, T. J. Bertus, Joseph A. Glick, W. P. Pratt, and Norman O. Birge, “Spin-valve Josephson junctions for cryogenic memory,” Phys. Rev. B 97, 024517 (2018).

[10] A. V. Ustinov and V. K. Kaplunenko, “Rapid single-flux quantum logic using π-shifters,” Journal of Applied Physics 94, 5405–5407 (2003).

[11] A. I. Buzdin, “Proximity effects in superconductor-ferromagnet heterostructures,” Rev. Mod. Phys. 77, 935–976 (2005).

[12] A. K. Feofanov, V. A. Oboznov, V. V. Bol’ginov, J. Lisenfeld, S. Poletto, V. V. Ryazanov, A. N. Rossolenko, M. Khabipov, D. Balashov, M. A. Zorin, P. N. Dmitriev, V. P. Koshelets, and A. V. Ustinov, “Implementation of superconductor/ferromagnet/superconductor π-shifters in superconducting digital and quantum circuits,” Nature Physics 6, 593 (2010).

[13] T. Kato, A. A. Golubov, and Y. Nakamura, “ decoherence in a superconducting flux qubit with a π-junction,” Phys. Rev. B 76, 172502 (2007).

[14] D. Massarotti, N. Banerjee, R. Caruso, G. Rotoli, M. G. Blamire, and F. Tafuri, “Electrodynamics of Josephson junctions containing strong ferromagnets,” Phys. Rev. B 98, 144516 (2018).

[15] M. Weides, M. Kemmler, E. Goldobin, D. Koelle, R. Kleinert, H. Kohlstedt, and A. Buzdin, “High quality ferromagnetic 0 and π Josephson tunnel junctions,” Applied Physics Letters 89, 122511 (2006), https://doi.org/10.1063/1.2356104.

[16] A. A. Bannykh, J. Pfeiffer, V. S. Stolyarov, I. E. Batov, V. V. Ryazanov, and M. Weides, “Josephson tunnel junctions with a strong ferromagnetic interlayer,” Phys. Rev. B 79, 054501 (2009).

[17] G. Wild, C. Probst, A. Marx, and R. Gross, “Josephson coupling and Fiske dynamics in ferromagnetic tunnel junctions,” The European Physical Journal B 78, 509–523 (2010).

[18] E. Terzioglu and M. R. Beasley, “Complementary Josephson junction devices and circuits: a possible new approach to superconducting electronics,” IEEE Transactions on Applied Superconductivity 8, 48–53 (1998).

[19] L. B. Ioffe, V. B. Geshkenbein, M. V. Feigel’man, A. L. Fauchère, and G. Blatter, “Environmentally decoupled sds-wave Josephson junctions for quantum computing,” Nature 398, 679–681 (1999).

[20] S. Kawabata, S. Kashiwaya, Y. Asano, Y. Tanaka, and A. A. Golubov, “Macroscopic quantum dynamics of π junctions with ferromagnetic insulators,” Phys. Rev. B 74, 180502 (2006).

[21] S. Kawabata, Y. Asano, Y. Tanaka, A. A. Golubov, and S. Kashiwaya, “Josephson π state in a ferromagnetic insulator,” Phys. Rev. Lett. 104, 117002 (2010).

[22] A. S. Vasenko, S. Kawabata, A. A. Golubov, M. Yu. Kupriyanov, C. Lacroix, F. S. Bergeret, and F. W. J. Hekking, “Current-voltage characteristics of tunnel Josephson junctions with a ferromagnetic interlayer,” Phys. Rev. B 84, 024524 (2011).

[23] R. Caruso, D. Massarotti, V. V., A. Ben-Hamida, N.L. Karelin, A. Miano, I. Vernik, F. Tafuri, V. Ryazanov, O. Mukhanov, and G. P. Pepe, “RF assisted switching in magnetic Josephson junctions,” Journal of Applied Physics 123, 133901 (2018).

[24] R. Caruso, D. Massarotti, A. Miano, V. V. Bolginov, A. Ben-Hamida, N.L. Karelin, G. Campagnano, I. Vernik, F. Tafuri, V. Ryazanov, O. Mukhanov, and P. G. Pepe, “Properties of ferromagnetic Josephson junctions for memory applications,” IEEE Transactions on Applied Superconductivity (2018), 10.1109/TASC.2018.2836979.

[25] S. Kawabata, A. Ozaeta, A. S. Vasenko, F. W. J. Hekking, and S.F. Bergeret, “Efficient electron refrigeration using superconductor/spin-filter devices,” Applied Physics Letters 103, 032602 (2013).

[26] Y. Zhu, A. Pal, M. G. Blamire, and Z. H. Barber, “Superconducting exchange coupling between ferromagnets,” Nature Materials 16, 195 (2016).

[27] J. P. Cascales, Y. Takamura, G. M. Stephen, D. Heiman, F. S. Bergeret, and J. S. Moodera, “Switchable Josephson junction based on interfacial exchange field,” Applied Physics Letters 114, 022601 (2019), https://doi.org/10.1063/1.5050382.

[28] K. Senapati, M. G. Blamire, and Z. H. Barber, “Spin-filter Josephson junctions,” Nature Materials, 849 (2011).

[29] Avradeep P., K. Senapati, Z. H. Barber, and M. G. Blamire, “Electric-field-dependent spin polarization in GdN spin filter
Josephson junctions with GdN barriers show a spin-filtering effect due to the simultaneous presence of tunnel conduction mechanisms and a magnetic exchange field $h$ in the ferromagnetic phase of the barrier. When the GdN becomes ferromagnetic ($T_{Curie} \sim 40 \text{K}$), the presence of exchange interactions leads to a spin selectivity of the tunneling processes: spin tunnel junctions,” Advanced Materials 25, 5581–5585 (2013), https://onlinelibrary.wiley.com/doi/pdf/10.1002/adma.201300636.

[30] Avradeep P., Z.H. Barber, J.W.A. Robinson, and M.G. Blamire, “Pure second harmonic current-phase relation in spin-filter Josephson junctions,” Nature Communications 3, 3340 (2014).

[31] D. Massarotti, A. Pal, G. Rotoli, L. Longobardi, M. G. Blamire, and F. Tafuri, “Macroscopic quantum tunnelling in spin filter ferromagnetic Josephson junctions,” Nature Communications , 7376 (2015).

[32] R. Caruso, D. Massarotti, G. Campagnano, A. Pal, H. G. Ahmad, P. Lucignano, M. Eschner, M. G. Blamire, and F. Tafuri, “Tuning of magnetic activity in spin-filter Josephson junctions towards spin-triplet transport,” Phys. Rev. Lett. 122, 047002 (2019).

[33] A. Barone and G. Paternò, Physics and Application of the Josephson Effect (John Wiley and Sons, 1982).

[34] K. K. Likharev, Dynamics of Josephson junctions and circuits (Gordon&Breach, 1986).

[35] M. H. Devoret, J. M. Martinis, D. Esteve, and J. Clarke, “Resonant activation from the zero-voltage state of a current-biased josephson junction,” Phys. Rev. Lett. 53, 1260–1263 (1984).

[36] J. M. Martinis, M. H. Devoret, and J. Clarke, “Experimental tests for the quantum behavior of a macroscopic degree of freedom: the phase difference across a Josephson junction,” Phys. Rev. B 35, 4682–4698 (1987).

[37] J. M. Martinis and R. L. Kautz, “Classical phase diffusion in small hysteretic josephson junctions,” Phys. Rev. Lett. 63, 1507–1510 (1989).

[38] R. L. Kautz and J. M. Martinis, “Noise-affected IV curves in small hysteretic Josephson junctions,” Phys. Rev. B 42, 9903–9937 (1990).

[39] M. H. Devoret and R. J. Schoelkopf, “Superconducting circuits for quantum information: an outlook,” Science 339, 1169 (2013).

[40] P. Krantz, M. Kjaergaard, F. Yan, T. P. Orlando, S. Gustavsson, and W. D. Oliver, “A quantum engineer’s guide to superconducting qubits,” Applied Physics Reviews 6, 021318 (2019), https://doi.org/10.1063/1.5089550.

[41] Y. C. Chen, M. P. A. Fisher, and A. J. Leggett, “The return of a hysteretic Josephson junction to the zero-voltage state: IV characteristic and quantum retrapping,” Journal of Applied Physics 64, 3119–3142 (1988).

[42] J. R. Kirtley, C. D. Tesche, W. J. Gallagher, A. W. Kleinsasser, R. L. Sandstrom, S. I. Raider, and M. P. A. Fisher, “Measurement of the intrinsic subgap dissipation in Josephson junctions,” Phys. Rev. Lett. 61, 2372–2375 (1988).

[43] R. Cristiano, L. Frunzio, C. Nappi, M. G. Castellano, G. Torrioli, and C. Cosmelli, “The effective dissipation in Nb/AlOx/Nb Josephson tunnel junctions by return current measurements,” Journal of Applied Physics 81, 7418–7426 (1997).

[44] V.K. Semenov, A.A. Odintsov, and A.B. Zorin, SQUID’85 - Fabrication and measurements of hybrid Nb/Al Josephson junctions and flux qubits with $\pi$-shifters,” Superconductor Science and Technology 28, 025009 (2015).

[45] K. Serniak, M. Hays, G. de Lange, S. Shankar, L. D. Burkhardt, L. Frunzio, M. Houzet, and M. H. Devoret, “Hot nonequilibrium quasiparticles in transmon qubits,” Phys. Rev. Lett. 121, 157701 (2018).

[46] J. Koch, Terri M. Yu, Jay Gambetta, A. A. Houck, D. I. Schuster, J. Majer, A. Blais, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf, “Charge-insensitive qubit design derived from the Cooper pair box,” Phys. Rev. A 76, 042319 (2007).

**Appendix A: The spin-filtering effect**

Josephson junctions with GdN barriers show a spin-filtering effect due to the simultaneous presence of tunnel conduction mechanisms and a magnetic exchange field $h$ in the ferromagnetic phase of the barrier. When the GdN becomes ferromagnetic ($T_{Curie} \sim 40 \text{K}$), the presence of exchange interactions leads to a spin selectivity of the tunneling processes: spin...
the temperature 15K at which we calculate the P
junction with t
Figure 8: Measured R
where R
resistance in the absence of magnetic exchange field, respec-
T
temperature semiconducting model fit (red straight line) above the Curie
magnetic phase of the barrier. This curve allows to obtain the
straight line is the semiconducting fit performed in the para-
spin-filter JJ with a GdN barrier thickness of 4
net magnetization in the superconducting electrodes of spin-filter
Fermi level [51].
The magnetic exchange field h in the barrier induces a magnetization in the superconducting electrodes of spin-filter
JJs [51]. The angles between the magnetization in the electrodes and the magnetic exchange field will be denoted as α and β [51]. Tunneling of spin-polarized carriers appears only if the angles α and β between h and the magnetization in the left and right superconducting electrodes, respectively, are different from 0 and π [Fig. 9] [51]. The quasiparticle current in non-magnetic devices (P = 0, h = 0), and in magnetic JJs with total spin polarization (P = 1, h < Δ, being Δ the superconducting gap of the electrodes) and maximum non-collinearity between h and the magnetization in the superconducting electrodes (α = β = π/2) has the same analytic expression, and the I−V curves are comparable [Fig. 9]. We verify this statement using the expression for the quasiparticle current in spin-
filter JJs proposed in [51]. This result justifies the use of a con-
ventional TJM model, in which there is no explicit introduc-
tion of a magnetic exchange field in the barrier, when fitting the I−V curves in the ideal case of perfect spin polarization.

$$P = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow},$$

(A1)

where σ_\uparrow (down) is the tunnel conductance through the barriers seen by spin up (down) carriers. In the limit of small magnetic exchange fields, the spin-filtering efficiency reduces to

$$P \sim \tanh \left( \coth^{-1} \left( \frac{R^*}{R} \right) \right),$$

(A2)

where R and R* correspond to the measured resistance and the resistance in the absence of magnetic exchange field, respectively [28].

In Fig. 8 we show the R(T) curve (black points) for the spin-filter JJ with a GdN barrier thickness of 4.0 nm. The red straight line is the semiconducting fit performed in the paramagnetic phase of the barrier. This curve allows to obtain the resistance in the absence of magnetic exchange field R*. Below T_{Curie} (dashed black line), we can observe a decrease in the resistance because one spin channel is favored in the con-
duction.

The spin-selective tunneling processes affect the normal resistance R_N too, which is defined as R_N = 1/(4π(\epsilon N(0))^2(\sigma_\uparrow + \sigma_\downarrow)), with N(0) density of state at the Fermi level [51].

The magnetic exchange field h in the barrier induces a magnetization in the superconducting electrodes of spin-filter

Figure 8: Measured R(T) curves (black points) and semiconducting model fit (red straight line) above the Curie
temperature T_{Curie} of the device (dashed black line) for the
junction with t = 4.0 nm. The dash dotted blue line indicates the temperature 15K at which we calculate the P.

Figure 9: Comparison between the normalized subgap branch J_{qp} = l_{qp}R_N/V for a non-magnetic tunnel JJ (red
straight line) and a perfect spin-filter tunnel JJ (black points). The expression of the quasiparticle current used for the
simulations can be found in [51]. The parameters used to reproduce the curves are: P = 0, h = 0, Δ = 1, η = 0.01Δ (damping factor) and T = 4.2 K for the non-magnetic
junction and P = 1, h = 0.4Δ, Δ = 1, η = 0.01Δ for the
spin-filter JJ. The angles α and β between h and the
magnetization induced in the superconducting electrodes are
α = β = π/2.