Conductance in Co|Al₂O₃|Si|Al₂O₃ Permalloy with asymmetrically doped barrier

R. Guerrero,² F. G. Aliev,² R. Villar,¹ T. Santos,² J. Moodera,² V. K. Dugaev,³ and J. Barnaś⁴

¹Dpto. de Física de la Materia Condensada, C-III, Universidad Autónoma de Madrid, 28049, Madrid, Spain
²Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
³Department of Physics, Rzeszów University of Technology, al. Powstańców Warszawy 6, 35-959 Rzeszów, Poland, and Department of Physics and CFIF, Instituto Superior Técnico, TU Lisbon, av. Rovisco Pais, 1049-001 Lisbon, Portugal
⁴Department of Physics, Adam Mickiewicz University, Umultowska 85, 61-614 Poznań, Poland; and Institute of Molecular Physics, Polish Academy of Sciences, Smoluchowskiego 17, 60-197 Poznań, Poland

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We report on dependence of conductance and tunnelling magnetoresistance on bias voltage at different temperatures down to 2K in Co|Al₂O₃(10Å)|Si(δ)|Al₂O₃(2Å)|Permalloy magnetic tunnel junctions. Complementary low frequency noise measurements are used to understand the conductance results. The obtained data indicate the breakdown of the Coulomb blockade for thickness of the asymmetric silicon layer exceeding 1.2Å. The crossover in the conductance, the dependence of the tunnelling magnetoresistance with the bias voltage and the noise below 80K correspond to 1 monolayer coverage. Interestingly, the zero bias magnetoresistance remains nearly unaffected by the presence of the silicon layer. The proposed model uses Larkin-Matveev approximation of tunnelling through a single impurity layer generalized to 3D case and takes into account the variation of the barrier shape with the bias voltage. The main difference is the localization of all the impurity levels within a single atomic layer. In the high thickness case, up to 1.8Å, we have introduced a phenomenological parameter, which reflects the number of single levels on the total density of silicon atoms.

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I. INTRODUCTION

The discovery of large tunnelling magnetoresistance (TMR) at room temperature \( \text{[1, 2]} \) has strongly renewed the interest in spin tunnelling phenomena. Up to very recently the main efforts were concentrated on the increase of tunnelling magnetoresistance values by using ferromagnetic electrodes with the highest possible spin polarization (half metallic ferromagnetism), searching for new types of insulating barriers (including the so called spin filters \( \text{[3]} \)), or a combination of both approaches, where the ferromagnetic/insulator interface design could also play an important role for spin polarized tunnelling. The last approach has recently provided an enormous progress in the TMR values at room temperatures. It has been demonstrated that in epitaxial Fe/MgO/Fe magnetic tunnel junctions (MTJ), where there exist conditions for coherent propagation of specific spin orbitals from one ferromagnetic electrode to the other one, TMR has reached experimentally values up to 410\( \% \) \( \text{[4]} \). This fact, supported by theoretical calculations predicting a TMR of more than 1000\( \% \) have further increased both the fundamental and technological interest in spin polarized tunnelling.

Another possible research direction, which remains however poorly explored, is related to tunnelling in complex (hybrid) junctions. Indeed, the manipulation of the barrier by doping with magnetic or nonmagnetic impurities, or inserting magnetic, for example see reference \( \text{[5]} \), nonmagnetic \( \text{[6]} \) (even superconducting \( \text{[6, 7]} \)) quantum dots (QD), would add a new degree of freedom to spin polarized tunnelling and strongly enhance the versatility of spintronic devices based on spin polarized tunnelling. Tunnelling in such hybrid, but non magnetic devices, has been intensively studied during the last two decades and especially in single electron transistors where the gate electrode is attached to quantum dots separated by two barriers each with a metallic contact (emitter and collector)\( \text{[8]} \).

Recent theoretical studies of hybrid spintronic devices with two ferromagnetic leads contacting single or double quantum dots have revealed plenty of new interesting phenomena related with the interplay between magnetic tunnelling processes and spin/charge accumulation on quantum dots. From the experimental side, some few groups have demonstrated that Coulomb interaction may indeed play an important role not only in ferromagnetic granular systems \( \text{[9]} \) (as occurs in the corresponding nonmagnetic analogs), but also in ferromagnetic single electron tunnelling devices constructed either from a 2D electron gas \( \text{[10]} \) or when a single metallic nanoparticle is contacted by ferromagnetic electrodes \( \text{[11]} \). It has also been reported that in ultrasmall nanoparticles, with a diameter between 5-10nm, their electronic structures (i.e. quantum effects) may also influence spin polarized tunnelling \( \text{[12]} \). Other interesting examples of spin polarized tunnelling in hybrid structures include ferromagnetic leads contacting carbon nanotubes \( \text{[13]} \) or a C60 molecule.
Actually, from the technological point of view, it is easier to attach ferromagnetic leads via tunnelling barriers to an array instead of to a single quantum dot. This method, despite the evident drawback due to some distribution in QD sizes and the corresponding charging energies, adds evident versatility to the design of the experiment, allowing continuous tuning between two different regimes: (i) weak doping regime where QDs are substituted by impurities and (ii) strong doping regime. In the second regime one would expect the QD charging energy to reduce continuously with the average dot size, allowing sequential electron transport through an otherwise blocked channel (Coulomb blockade) in addition to direct tunnelling.

Therefore, the knowledge of different mechanisms affecting the conductance, and especially its dependence on the applied bias, could be an important instrument for a comparative analysis of noise and transport. We should, however, note that the bias dependence of conductivity and TMR in real magnetic tunnel junctions, is still poorly understood. The most accepted model [15], which does not take into account the possible defects inside the barrier, predicts an attenuation of the polarization due to the decrease of the difference between the height of the barrier and the bias voltage. However, the observed reduction in conductivity usually exceeds the predicted effect.

Two theories have been developed in order to explain the anomalous reduction in TMR. The first one explores the existence of impurity states, which reduce the spin current polarization and influence the conductance of the junctions at low bias [16]. The second one involves inelastic tunnelling as the main origin of unpolarized current [17]. This point of view has been also supported by the measurement of inelastic tunnelling in magnetic tunnel junctions [18]. Later on Ding et al. [19] have also detected a tunnelling magnetoresistance in vacuum based magnetic tunnel junctions with a reduced dependence on the bias voltage. These results indicate a possible influence of the impurity states on the polarization of the tunnel current.

For the nonmagnetic tunnel junctions with (nonmagnetic) nanoparticles inside the barrier the presence of a zero bias anomaly was first reported and explained by Giaever [20]. The main mechanism responsible for the appearance of the threshold voltage is Coulomb blockade, which controls two steps tunnelling. In this model the threshold voltage is distributed from 0 V to a maximum voltage $V_N$. In the doped tunnel junctions $V_N$ is given by the size of the doping particles, which determines a charging energy, given by the capacitance of the particles. This provides some distribution in the population of electrons inside the particles.

The two steps tunnelling in a magnetic tunnel junction has been later treated using the other method developed by Glazman and Matveev [21, 22]. This theory states that the current is defined, in each particle, by the tunnelling rates from one of the electrodes to the central particle, and from the island to the other electrode. As soon as conductance and spin current polarization are modified, a modification of the dependence on voltage of the tunnelling magnetoresistance may be expected. Indeed, when the bias voltage is increased, the number of allowed two steps processes is also increased.

Previouly to this work, Jansen et al. [23] studied MTJs with Si nanoparticles up to 1.8Å introduced in a symmetric position. They observed gradual suppression of tunnelling magnetoresistance. In the present work Si particles were introduced asymmetrically inside the barrier. While symmetric doping effectively separates the barrier into two parts with similar tunnelling rates, the asymmetric doping is expected to affect weakly the largest tunnelling rate minimizing the influence of the nonmagnetic Si doping (at least for relatively weak doping levels).

This work presents an experimental study of electron transport in Co(100Å)/Al$_2$O$_3$(10Å)/Si(δ)/Al$_2$O$_3$(2Å)/Py(100Å) hybrid magnetic tunnel junctions, where the largest barrier is 5 times larger than the short one. We observed a continuous transition between the weak (Si impurities) and strong (array of Si quantum dots) regimes. In order to discriminate the different conductance regimes, we study the temperature and bias dependence of both the conductivity and TMR as a function of Si doping.

II. EXPERIMENTAL DETAILS.

Details of sample preparation have been published previously [23-24]. For silicon doped samples, the tunnel barriers were deposited in two steps. After deposition of the underlying Co electrode, a first tunnel barrier was formed by deposition and subsequent oxidation of 10 Å of Al. Subsequently, sub-monolayer amounts of Si (δ in the following) were deposited on the Al$_2$O$_3$ surface, followed by a second Al layer deposition (2 Å) and oxidation, resulting in a “δ-doped” Al$_2$O$_3$/Si/Al$_2$O$_3$ tunnel barrier. After the deposition of the barrier 100 Å of permalloy were deposited, in order to form the second magnetic layer. All the samples thicknesses were measured using a quartz monitor. The quality of the Al layers and the Al$_2$O$_3$ has been previously tested in Ref. [24]. In the following the positive bias voltage corresponds to the application of the voltage in the top electrode, while the negative to application of the voltage in the bottom one.

Measurements were performed using a computer controlled system [26], which allows to detect the dynamic resistance, the DC value of the current and the voltage, and the noise in the device under study. Biasing of the samples was done at a constant current, applied using a calibrated source. It also allowed to modulate the applied current. A square waveform was used in order to detect the transfer function of the line and the dynamic resistance of the junctions. The voltage response of the
devices was amplified by using DC coupled low noise amplifiers. The amplified signal was recorded in an analog-digital converter.

The measurement of the noise uses the same biasing technique and the same low noise amplifiers, which were placed in the top part of a cryostat. The pre-amplified signals are further amplified by additional low-noise amplifiers (Stanford Research SR560). A spectrum analyzer SR780 calculates the cross-correlation spectrum of the voltage noise, containing thermal, shot and $1/f$ contributions. The obtained dynamic resistance allows to convert the voltage noise into the current noise. Extrinsic noise, introduced by the amplifiers and the current source, was removed by using the data extracted from a careful calibration performed on resistors at low temperatures. In the experiments we measured 9 different samples, 2 of each Si thickness, except for $\delta=0.6\text{Å}$ where we only characterized 1.

III. CONDUCTANCE, ZERO BIAS ANOMALY AND TUNNELLING MAGNETORESISTANCE

At room temperature the dependence of the conductance on the bias voltage fits well to a parabolic function (see inset to Fig. 1(b)). The parabolic dependence of the conductance, being due to direct tunnelling, was explained within the Brinkman-Dynes-Rowell (BDR) model [27], which describes the tunnelling conductance as a function of the parameters of a trapezoidal barrier: the width, the average height and the difference between the sides of the barrier, such difference being known as asymmetry.

The results of the fits are plotted in Fig. 1 showing in general an increase of the barrier width with Si doping. However, the increase of the width does not correspond with the deposited Si thickness. As to the height of the barrier, it clearly diminishes when the silicon is introduced inside the barrier. At present we have no clear explanation for this reduction. One of the possible reasons could be some decrease of the work function of the aluminium oxide. This explanation, however, contradicts the observed variation of the barrier asymmetry (Fig. 1), which decreases with the thickness of the Si layer. The disagreement between the deposited thickness and the obtained parameters using the BDR model could be attributed either to the simplification made by the model, which assumes a trapezoidal barrier, a parabolic band structure and the WKB approximation, or to defects inside the barrier that should diminish the barrier height. However the obtained results present evidence that the Si layer affects the barrier properties beyond the errors committed in the estimation procedure.

The tunnelling resistance of the studied Si doped MTJs measured at $T=2\text{ K}$ and $T=300\text{ K}$, in the zero bias limit, is plotted in Fig. 2. The observed enhancement of the resistance when the temperature is lowered rules out the presence of pinholes even for the highest silicon thickness [28, 29]. There is an increase of the resistance for $\delta \geq 1.5\text{ Å}$, both at room and low temperatures, whereas at lower concentrations the resistance trend is to decrease. This fact indicates a change of the regime in the conductance, which will be further confirmed in the dependence of the conductance on the bias voltage and the TMR.

A. Dependence of the conductance on the voltage at low temperatures

While at room temperature conductance is a parabolic function of the bias, at low temperatures (below 100 K), the dependence of conductance on the bias changes substantially. On the one hand, all MTJs at low biases ($V \lesssim 30\text{ mV}$) present a peak in the resistance. Usually such a peak is called zero bias anomaly (ZBA). On the other hand, high bias conductance regimes (above 100 mV) show a strong variation with silicon thickness.

To show more clearly the qualitative change of conduc-

FIG. 1: Barrier parameters evaluated using the BDR model. The graph (a) shows the barrier width and height in the left and the right axis, respectively, as function of the Si thickness. In the graph (b) is shown the asymmetry also as function of the Si thickness. In the inset we present the typical dependence on voltage of the conductance at room temperature. The dashed line is a parabolic fit used to extract the parameters plotted in the graph (a) and (b).

FIG. 2: Resistance of the MTJ’s at low temperature, graph (a) and room temperature, graph (a), as a function of the Si thickness ($\delta(\text{Å})$). The lines in the graphs are guides to the eyes.
tance regime with Si doping we present the bias dependence of the normalized conductance

\[
ZBA(\%) = 100 \times \frac{R(100\text{mV}) - R(0\text{mV})}{R(100\text{mV})}
\]

(1)

The dependence of ZBA vs. Si thickness, plotted in Fig. 4, shows that the resistance peak, being weakly dependent on \(\delta\) for low Si thickness, strongly increases for the high doping region. The crossover region corresponds to the thickness of approximately \(\delta=1.2\ \text{Å}\).

The experimental data presented above may be understood within the two-step model as follows. If the formation of silicon islands starts for a Si thickness \(\delta=1.2\ \text{Å}\), then the enhanced resistance peak (ZBA) could be attributed to the appearance of a new energy scale in the electron transport through the barrier, related with the finite electron capacitance of the silicon islands, being practically absent for the small Si thickness range. This hypothesis is supported by the plot of the normalized bias voltage dependence of the conductance, Fig. 3. Clearly in the conductance of the junctions with higher Si doping levels there is a crossover at a certain voltage. At higher voltage the dependence of the conductance becomes less pronounced, whereas the junctions with low doping maintain the same behavior, as expected in a non-doped tunnel junction with electron transport due to direct tunneling.

The change of the conductance regime is also evident from comparison of the lower bias conductance for undoped MTJs and those with highest Si doping (corresponding to \(\delta=1.8\ \text{Å}\)). As can be seen in the (b) graph in Fig. 3 both curves show structure in \(G(V)\) at low bias close to \(V=30\ \text{mV}\). The similarity of these weak anomalies both for the undoped and doped MTJs indicate their common origin, most probably related with electron conduction mechanisms through the aluminium oxide barrier.

We have observed that generally, for all MTJs studied, the low bias conductance varies linearly with temperature at low temperatures (\(T<20\ \text{K}\)). Within the Coulomb blockade model this could be attributed to a variation in the thermally activated population of electrons inside the islands, which determines the slope of the conductance at zero bias. In brief, the conductance at zero bias and low temperatures could be expressed as

\[
G(0, T) \propto \int_0^\infty n(V_{Ch}) e^{-\frac{eV_{Ch}}{k_B T}} dV_{Ch} \sim n(V_{Ch} \sim 0) \frac{k_B T}{e}
\]

(2)

where \(eV_{Ch}\) is the charging energy needed to introduce an electron in the metallic layer. At \(V=0\ \text{V}\) the number of charged islands is given by the exponential term. Then, at low temperatures, the conductance is proportional to the number of charged particles in thermal equilibrium \(n(0)\). Although the temperature dependence of conductivity of the different MTJs studied varies in nearly two orders of magnitude, the normalized (to 2 K) low temperature slope in the linear dependence of conductivity vs. temperature was found to be much weaker dependent on the silicon thickness, with an average value of \((5 \pm 3) \times 10^{-4}\ \text{K}^{-1}\) but with a rather large dispersion (Fig. 4).

B. Tunneling magnetoresistance

The dependence of the tunnelling magnetoresistance on Si thickness is shown in figure 4. This plot represents the zero bias tunnelling magnetoresistance, obtained by using the following definition of TMR.

\[
T(\text{P}) = \frac{G(0, T)_{\text{P}}}{G(0, T)_{\text{AP}}} 
\]

\[
T(\text{AP}) = \frac{G(0, T)_{\text{AP}}}{G(0, T)_{\text{P}}} 
\]

\[
ZBA(\%) = 100 \times \frac{R(100\text{mV}) - R(0\text{mV})}{R(100\text{mV})}
\]

(1)

FIG. 3: Dependence of the conductance on the bias voltage at \(T=2\ \text{K}\). The curves are normalized by the conductance measured at 0mV in each curve. The plot (a) presents data up to high bias, where a mechanism related to the formation of Si islands becomes important (see the text). The graph (b) presents the low bias behavior, showing the presence of the same zero bias anomaly at \(V\lesssim 30\text{mV}\).

FIG. 4: Dependence of the quantity \(ZBA\) (defined in the text) on silicon thickness at \(T=2\ \text{K}\) in the parallel (P) and the antiparallel (AP) magnetic state. The increased \(ZBA\) at higher doping layers reflects a different behavior, related with the formation of Si islands.
was observed for a Si thickness of $\delta$ at low temperatures (of about 10 fect by the silicon. The step-like reduction of TMR values, however, remain nearly unaf-

The analysis of bias dependence of TMR which follows further supports our hypothesis. In order to analyze the bias dependence of TMR as a function of Si thickness, we have found the voltage needed to suppress a TMR to its half (zero bias) value (i.e. to TMR(0 V)/2). This parameter, called $V_{\text{TMR/2}}$, plotted as a function of the silicon thickness. Evidently, there is a crossover from a nearly constant $V_{\text{TMR/2}}$ regime below $\delta = 1.2 \, \text{Å}$, to a strongly decreasing one $V_{\text{TMR/2}}$ as a function of $\delta$, for Si thicknesses above one monolayer. The low Si doping regime with nearly constant $V_{\text{TMR/2}}$ proves the presence of two step tunnelling through localized states, with character and density of states nearly unchanged up to Si thickness of 1.2 Å.

When $\delta \geq 1.2$ seems that the effective capacitance corresponding to localized states inside the barrier is reduced, increasing dramatically the number of states available inside the barrier for tunnelling. The new transport channels serve as a source of unpolarized current, which explains the much stronger voltage dependence of TMR for large Si doping.

**IV. THEORETICAL MODEL**

To account for the above discussed experimental features of electronic transport in tunnel junctions, we calculate now theoretically transport characteristics as a function of bias voltage $V$ using the model of rectangular tunnelling barrier with a thin layer of impurities (Si atoms) which create a number of impurity levels inside the bar-
bias voltage. A low value of \( V \) quantifies the dependence of the magnetoresistance on the bias voltage. A low value of \( V_{TMR/2} \) means a strong dependence on bias voltage, while a high value means a weak one. We observe a diminished value of \( V_{TMR/2} \) when the ZBA starts to increase (see Fig. 3).

Barrier. In the limit of low density of Si levels, the current is due to direct tunneling in each spin channel, and the current density can be calculated from the formula

\[
j(V) = \frac{e}{4\pi^2\hbar} \sum_{\sigma} \int_0^{[2m(\epsilon-V_\sigma)]^{1/2}/\hbar} dk_l dk_i |t_{ki}|^2 \times \left( \frac{\epsilon - \hbar^2 k_i^2/2m - V_\sigma}{\epsilon - \hbar^2 k_i^2/2m - V_\sigma} \right)^{1/2} \left[ f(\epsilon) - f(\epsilon - eV) \right],
\]

where \( k_i \) is the in-plane wavevector component of an electron incident on the barrier, \( t_{ki} \) is the transmission amplitude for an electron with wavevector \( k \) and spin \( \sigma \), with \( V_\sigma \) and \( V_{\sigma0} \) are the spin-dependent energy band edges on the left and right sides of the junction, respectively, which depend on the applied voltage as \( V_{\sigma0} = V_{\sigma0} + eV/2 \) and \( V_{\sigma} = V_{\sigma0} - eV/2 \) (here \( V_{\sigma0} \) and \( V_{\sigma0} \) are the corresponding band edges at zero voltage). Apart from this, the integration in Eq. (4) is over the electron energy \( \epsilon \), and \( f(\epsilon) \) is the Fermi-Dirac distribution function.

To calculate the tunneling probability for a nonzero voltage applied to the system we use a semiclassical approximation for the wavefunction inside the barrier with a slope of potential. This is justified in case when the variation of the barrier height \( V_0 \) is small at the electron wavelength \( \lambda \sim \hbar/(2mV_0)^{1/2} \), which restricts the bias voltage to \( |eV| \ll m^{1/2}V_0^{3/2}L/\hbar \), where \( L \) is the barrier width.

\[4\]

A. Impurity-mediated tunneling

As the density of impurities grows, an additional mechanism of tunneling through the impurity levels inside the barrier becomes more effective than the direct tunneling. In the frame of the Larkin-Matveev [22] model, the resonant tunneling through the structure is described by the transition probabilities \( w_{kp} \). More specifically, \( w_{kp} \) is the probability of transition from the state described by the wavevector \( p \) on the left side of the barrier to the state corresponding to the wavevector \( k \) on the right side (from now on we drop the spin index \( \sigma \) referring to the tunneling in different spin channels), and is given by the formula

\[
w_{kp} = 2\pi \left[ \sum_i \frac{T_{ki}T_{i\bar{p}}}{\epsilon_{\bar{p}} - \epsilon_i + \Gamma_i} \right]^2 \delta(\epsilon_{\bar{p}} - \epsilon_k),
\]

where \( T_{pi} \) and \( T_{ik} \) are the matrix elements for transitions between the states of the corresponding leads and of the i-th impurity, whereas \( \Gamma_i \) is the width of the impurity level associated with tunneling from the localized level through the barrier. The sum in Eq. (3) runs over all impurities. The \( i \) factor is the imaginary unit.

An important point is that the matrix elements \( T_{pi} \) and \( T_{ik} \) include a phase factor depending on the location of the impurity inside the barrier.

\[
T_{ki} = \frac{1}{S^{1/2}} e^{-ik_0 R_l} e^{ik_\zeta(z_1 - L/2)} \frac{\hbar^2}{m} (2\pi\kappa)^{1/2},
\]

\[
T_{i\bar{p}} = \frac{1}{S^{1/2}} e^{i\bar{p}_0 R_l} e^{-\bar{p}_\zeta(z_1 + L/2)} \frac{\hbar^2}{m} (2\pi\kappa)^{1/2},
\]

where \( S \) is the junction area, \( R_l \) and \( z_1 \) are the in-plane and out-of-plane components of the i-th impurity position, \( k \equiv (k_i, ik_\zeta) \) (and similarly for \( p \)), while \( \kappa \) is the inverse localization length of the impurity wavefunction. We assume that the impurities are randomly distributed in the plane, i.e. \( R_l \) is a random variable, whereas \( z_1 \) is the same for all impurities.

Assuming that the energy level \( \epsilon_i \) and the level width \( \Gamma_i \) do not depend on the position \( R_l \), and averaging over \( R_l \) in the plane, we obtain the following formula for the electric current:

\[
j(V) = \frac{2\pi e}{S\hbar} \sum_{\sigma} \sum_{k,p} \left| \sum_i T_{ki}T_{i\bar{p}} \right|^2 \delta(\epsilon_k - \epsilon_p) \left[ f(\epsilon_k) - f(\epsilon_k - eV) \right].
\]

After calculating the average \( \left| \sum_i T_{ki}T_{i\bar{p}} \right|^2 \), one finds that the current density \( j \) in the resonance-impurity channel consists of two terms, and can be written as

\[
j(V) = \frac{2\pi e}{\hbar} \sum_{\sigma} \sum_{k,p} n \left| T_{ki} \right|^2 \left| T_{i\bar{p}} \right|^2 \frac{1 + n \delta(k_i - p_i)}{\left( \epsilon_k - \epsilon_i^2 \right)^2 + \Gamma_i^2} \delta(\epsilon_k - \epsilon_p) \left[ f(\epsilon_k) - f(\epsilon_k - eV) \right],
\]

where \( n \) is the electron density in the left lead.
The first term in Eq. (9) is linear in the 2D impurity density \( n \) and describes the transitions through completely isolated single levels. Such transitions do not conserve the in-plane components of \( \mathbf{p} \) and \( \mathbf{k} \). The second term in Eq. (9) is nonlinear in \( n \) and describes the electron transitions through the impurity plane. For such transitions the corresponding in-plane components of electron wavevectors are conserved.

In our calculations we include all three channels. The total conductance per unit area, \( G/S \), is presented in Fig. 8 for parallel magnetic configuration and for indicated impurity concentrations. The width of the tunnel barrier is taken as \( L = 1.2 \) nm, and the Si atoms are located within the plane of \( z = -0.4 \) nm, measured from the center of the barrier. The energy structure corresponds to the majority and minority bands in Co, \( E_{F\uparrow} = 4.5 \) eV and \( E_{F\downarrow} = 0.66 \) eV, respectively. The height of the barrier is assumed to be \( V_0 = 1 \) eV. In turn, in Fig. 9 we show the reduced conductance, \( G(V)/G(0) \).

It should be noted that the conductance as well as the reduced conductance are slightly asymmetric with respect to bias reversal, see Fig. 8 and Fig. 9. This asymmetry is here associated with tunneling through single impurity levels which are located asymmetrically within the barrier. In our calculations we assumed that the impurities are located in the barrier close to the interface between the barrier and one of the electrodes - like in experiments discussed above. Such an asymmetry of impurity position with respect to the center of tunnel barrier leads to the asymmetry of the conductance \( G(V) \).

### B. Role of Coulomb interaction

When the density of impurity levels \( n \) grows, the conductance calculated within the model described above and including both direct and impurity-mediated tunneling increases monotonically (see Fig. 8). The experimental data (Fig. 2), however, reveal a rather sharp increase of the resistance to much higher values when the density \( n \) crosses a critical value \( n_{cr} \) corresponding to nearly complete filling of one atomic layer with Si atoms. The results for TMR presented in Figs. 6 and 7 also show that the physics of tunneling is substantially different for the density of Si atoms corresponding to complete filling of the plane.

We assume that the physical reason of such transition is related to a dramatic increase of the role of Coulomb interaction in the conductance through the Si levels. This effect can be also described by the decrease of the number of active levels, which are able to transmit electrons through the barrier. Indeed, if some Si atoms form a small cluster, then the cluster of several atoms acts as a single level for transmission because the Coulomb interaction prevents two or more electrons to occupy the same cluster. Thus we can assume that Eq. (9) describes the conductance as a function of the density of effective levels, \( n \rightarrow n_{ef} \), corresponding to the number of impurity clusters. As the density of Si atoms approaches the critical value \( n_{cr} \), the value of \( n_{ef} \) decreases rapidly. If \( n > n_{cr} \) and the density of Si atoms keeps growing then it corresponds to increasing thickness of the layer completely filled with the Si atoms. In such a case the Coulomb interaction is suppressed as there are no small clusters anymore, and the conductance can be described using a model of three-layer structure with well-defined properties of each of the layers. One can expect that the properties of the Si layer in such a structure are close to those of layered amorphous Si.

It should be emphasized that the direct tunneling is also suppressed in the vicinity of \( n \sim n_{cr} \). This is related to the Coulomb repulsion of electrons transmitted through the barrier from the charged impurity clusters, so that the electrons can tunnel through the barrier only in those areas, which are free from the impurity clusters or islands. One can describe this by a local increase of the tunneling barrier in the areas filled with clusters. This effectively leads to an increase of the average tunneling
Using the above described ideas we have calculated the resistance as a function of $\delta$, taking into account all three channels of conductivity as described above, but instead of the number of impurities $n$ we put in Eqs. (8), (9) an effective number of levels $n_{e,f}$, which we assumed to change rapidly from $n_{e,f} = n$ at $n < n_{cr} \approx 1.1 \times 10^{14} \text{ cm}^{-2}$ to a constant value $10^{13} \text{ cm}^{-2}$. We also corrected the contribution due to direct tunneling making it strongly dependent on $n$ in the vicinity of the transition point $n = n_{cr}$. More specifically, we reduced this contribution for $n > n_{cr}$ by modeling the dependence of the tunnel barrier $V_0$ on $n$: for $n < n_{cr}$ we take $V_0 = \text{const}$ independent of $n$ but for $n > n_{cr}$ we assume that this value increases by 0.6 eV, which corresponds to suppression of the direct tunneling due to the 'screening' from the large impurity clusters within the Si layer. The results for the resistance as a function of $\delta$ are presented in Fig. 10. As one can note, the theoretical curve is qualitatively similar to the experimental one.

Further improvement of the model can be made by taking into account the dependence of the impurity density of states $\nu$ on energy in the vicinity of the Fermi level, $\epsilon = \mu$. One can assume that the function $\nu(\epsilon)$ has a minimum near $\epsilon = \mu$ in accordance with the shape of the density of states (DOS) in amorphous Si (see, for example, Refs. [32, 33]). The DOS profile in the vicinity of the minimum at $\epsilon = \mu$ in amorphous a-Si can be approximately presented as a sum of the DOS tails related to the conduction and valence bands, $\nu(\epsilon) \approx \nu_0 \left( e^{-\left(\epsilon-\mu-\Delta\right)/\varepsilon_0} + e^{\left(\epsilon-\mu-\Delta\right)/\varepsilon_0} \right)$, where $\Delta \approx 0.25 \text{ eV}^{-1} \text{ atom}^{-1}$, and $\varepsilon_0 \approx 100 \text{ meV}$. In the vicinity of the minimum at $\epsilon = 0$ one can use the parabolic approximation

$$\nu(\epsilon) \approx \nu(\mu) \left( 1 + \frac{(\epsilon-\mu)^2}{2\varepsilon_0^2} \right)$$

(10)

where $\nu(\mu) = 2\nu_0 e^{-\Delta/\varepsilon_0}$.

After substituting the constant DOS $\nu(\mu)$ by the approximate function (10) with $\varepsilon_0 = 100 \text{ meV}$, we finally find the dependence presented in Fig. 11. The calculated dependence shown in Fig. 11 is in reasonable qualitative agreement with the experimental curves Fig. 3.a.

V. DISCUSSION

Several attempts have been made previously trying to understand the possible role of Coulomb blockade in the tunnelling current and magnetoresistance for ferromagnetic leads contacting a quantum dot [35, 36]. These works predict an oscillation in TMR(V) with a period given by the charging voltage. Experimentally, for tunnelling through an array of dots, the oscillatory behaviour has been reported only for the magnetic tunnel junctions with a barrier doped with cobalt nanoparticles. Those junctions had rather small ferromagnetic electrodes area $A=0.5\times0.5 \text{ \mu m}^2$ with the conduction almost completely blocked at low bias [3], and TMR oscillating with the period predicted theoretically. Other experiments, which also studied spin dependent electron transport through arrays of dots doping the barrier of magnetic tunnel junctions, have reached conclusions in respect to conductance similar to those reported here, i.e. observation of a non-oscillating increase of the conductivity with bias, when Coulomb blockade is suppressed by the applied voltage [3, 6, 19, 27].

The above cited reports employed different devices in order to study spin dependent tunnelling through a medium controlled by Coulomb blockade, and two of them specifically Ref. [5] and Ref. [9] used qualitatively similar magnetic tunnel junction devices. In these papers a granular film, consisting of nanometer size cobalt particles (with radius close to $\approx 2.5 \text{ nm}$) was embedded in a matrix of aluminium oxide. This array of Co dots was deposited on top of the aluminium oxide barrier (2.7nm in the first case [3] and 1-2 nm in the second one [9]) and was covered by the second aluminium oxide barrier. The top barrier was different in the studies mentioned above. While the first paper [3] used a $\approx 1.5 \text{ nm}$ thick secondary
RTN has been previously reported for nonmagnetic tunnel junctions and some other devices such as field effect transistors or quantum dots connected to metallic leads \[38\]. As to the tunnel junctions, RTN has been usually attributed to resistance fluctuations due to a single or few fluctuators \[39\]. The RTN was usually found for rather small area (below 1 µm²) junctions and low temperatures, because in this case the tunnel resistance is controlled by a few fluctuating defects, providing two-state fluctuations of the resistance. In the case of rather large tunnel junctions, as in the present study, the observation of RTN could not be described by the above models, involving direct influence of single or few defects fluctuations on the resistance. A non-uniform current distribution, induced by pin-holes, which are a source of "hot spots" just before the MTJs are broken down by the intensity of current, would neither explain the observed voltage dependence of the RTN. Indeed, our experimental data, particularly the current-voltage characteristics and the temperature dependence of the conductance show absence of pinholes and the above mentioned "hot spots".

As discussed above, for thick enough silicon layers δ > 1.2 Å the effective capacitance of the Si dots becomes small enough to break down the Coulomb blockade above a certain bias voltage. This increases the electron population of the island due to the two steps tunnelling events and enhances the tunnelling conductance.

It is evident that in the system under study the capacitance of the Si dots and, correspondingly, the Si dots population, should be distributed over the MTJ area, providing a possible variation of the local tunnelling current as a function of the spatial coordinate. In addition, the two-level systems situated close to the Si dots seem to introduce also time dependent fluctuations or RTN in the tunnelling current through these dots. The unavoidable dependence of the tunnelling current on the coordinate may enhance the effective contribution to the overall conductance from only a few fluctuators, resulting in a noise contribution additional to 1/f due to effective "amplification" of some conductance fluctuations responsible for RTN from these few defects. This is represented schematically in the Fig. 13 the change in the charge in the defect yields two states with different tunneling rates (τ), hence different conductance. The origin of the different times lies in the different levels inside the dots, which are determined by the capacitance, thus by the local environment. Of course, in our tunnel junction there are many defects, but at low temperatures there are only several of them active because the trapping-detrapping process uses to be thermally activated.

VI. CONCLUSIONS

To conclude, we have carried out an extensive study of electron transport in Co/Al₂O₃/Py magnetic tunnel junctions asymmetrically doped with Si. Our experimental data suggest that the observed behaviours of conduc-
FIG. 13: Schematic explanation of the noise observed at low temperatures. The presence of traps in our barrier modifies the levels inside our dot. This effect leads to two resistance states depending on what is the state of the defect. This effect is visible at low temperatures because only few processes are activated, hence the noise is RTN type as is clearly seen in Fig. 12.

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