Relevant energy scale in hybrid mesoscopic Josephson junctions

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Abstract

Transport properties of high quality Nb/semiconductor/Nb long Josephson junctions based on metamorphic In$_{0.75}$Ga$_{0.25}$As epitaxial layers are reported. Different junction geometries and fabrication procedures are presented that allow a systematic comparison with quasiclassical theory predictions. The impact of junction transparency is highlighted and a procedure capable of yielding a high junction quality factor is identified.
Superconductor/semiconductor hybrid devices are of much interest not only for their potential for electronic-device implementation but also as model systems for the investigation of the phenomena regulating the conversion of supercurrent into normal current at the interface through Andreev reflection [1]. By taking advantage of the increasing availability of ultra pure nanoscale semiconductors, major advances on the understanding of the microscopic nature of Josephson coupling and the interplay between superconductivity and mesoscopic effects can be expected [2, 3, 4]. Recent examples are the demonstration of the control of Josephson current in diffusive InAs nanowires coupled to superconducting leads (J-dot) [3] and the study of the interplay between quantum interference effects and superconducting correlation [5, 6]. Arguably, the main limiting factor for the exploitation of hybrid systems in practical devices is the low value of the junction quality factor $I_C R_N$ (i.e. critical current value times normal resistance). In fact, with few exceptions [7, 8], this is the parameter normally referred to in the literature [9, 10, 11]. It is crucial to have the largest possible value of $I_C R_N$, since, for instance, the maximum voltage amplification that can be obtained from a Josephson-Fet [12] or a J-Dot [3] is proportional to $I_C R_N$. The values of $I_C R_N$ found in experimental works, however, are far from those predicted by theory. This rises several issues about the actual nature of these junctions and motivated transport analysis such as the one reported here.

The reduction of $I_C R_N$ for semi/super Josephson junctions was already discussed in terms of reduced dimensionality of the normal conductor [13], low transparency of semi/super interfaces [14], diffusive interface [10], and decoherence effects [9]. In a recent work Hammer et al. studied superconductor-normal-superconductor (SNS) junctions with non-ideal S/N interfaces [15]. These authors predicted that the Thouless energy ($E_{th}$) is replaced by the proximity induced gap in the normal region as the relevant energy scale governing, for instance, the temperature dependence of the critical current (In a diffusive system with ideal transparent interfaces $E_{th} = \hbar D/L^2$).

The objective of our work is two-fold: i) to investigate experimentally the theoretical predictions on the impact of the actual transparency of SN interfaces on SNS systems and ii) to identify a processing strategy capable of yielding high quality junctions. We shall examine various junctions characterized by different transparencies and N regions of various length and compare experimental Ic vs T curves for different fabrication processes. From these curves, thanks to the knowledge of the parameters of N material, we shall be able
to analyze our data in the frame of ref. 15 and identify the process yielding the maximum interface transparency. In particular, we report a semiconductor/superconductor interface configuration for which $I_C R_N$ is close to 0.5mV for a junction length of 400nm, among the best results ever obtained for such hybrid devices.

In the hybrid devices of interest here, the normal conductor is an epitaxial layer of In$_{0.75}$Ga$_{0.25}$As bulk-doped with silicon. Thickness is in the 50nm-200nm range. Structures were grown by molecular beam epitaxy (MBE) on a GaAs (100)-oriented substrate 16. A sequence of In$_x$Al$_{1-x}$As layers of increasing In content was first deposited in order to ensure lattice matching with the upstanding layer of In$_{0.75}$Ga$_{0.25}$As. Before Nb deposition we performed a two-step surface cleaning of the semiconductor consisting of a first wet removal of the native oxide using diluted (1/50) HF solution and a subsequent vacuum RF discharge cleaning at very low power in Argon. Nb was then sputtered in situ during the same vacuum cycle and electrodes were defined by lift-off. All Nb films were 85nm thick. We shall call the device obtained with this process type “A” (Fig. 1-a). Type “A” (Junctions J1 and J2 reported in Table I) were fabricated on a 200nm thick epilayer with charge density $1.32 \times 10^{24}$m$^{-3}$ and mobility 0.69m$^2$/Vs at 1.5K in the dark. A second type of device was fabricated on 50nm thick epitaxial layers with charge density $n = 2.52 \times 10^{24}$m$^{-3}$ and mobility $\mu =0.52$m$^2$/Vs. We defined the semiconductor geometry (junction width) by employing a negative e-beam resist as a mask and subsequent wet chemical etching in H$_2$SO$_4$/H$_2$O$_2$/H$_2$O solution. This type of device will be labeled “B” and is showed in Fig. 1-b. A third type (“C”, shown in Fig. 1-c) of junction was obtained realizing the semiconductor mesa before Nb deposition. A Ti mask is first defined on the substrate by e-beam lithography, Ti thermal evaporation and lift-off. In$_{0.75}$Ga$_{0.25}$As structures are then defined by reactive ion etching. The last step is Nb deposition using the same technique described for type “A”. For type “C” we employed the same epitaxial layers of type “B”. For all samples the transition temperature of Nb leads is $T_c = 8.7$K, from which, using $\Delta_S = \Delta_{Nb} = 1.9k_B T_c$, we calculate $\Delta_{Nb} = 1.37$mV.

Measurements were performed as a function of temperature down to 250mK in an $^3$He cryostat. Current and voltage leads were filtered by RC filters at room temperature. A second filtering stage consisted of RC + copper-powder filters thermally anchored at 1.5K-1.9K. The last copper-powder filter stage was at 250mK, thermally anchored to the $^3$He pot. The shielding from magnetic field was ensured by a combination of nested cryoperm, Pb
FIG. 1: Panels a), b) and c) report schemes of type A, B, C junctions respectively: GaAs substrate (black), AlInAs graded buffer (dark green), In$_{0.75}$Ga$_{0.25}$As epitaxial layer (brown), Niobium (gray). Panel d), e) and f) show I-V curves at $T = 250$ mK of junctions J1, J4, and J5 (see Table I).
FIG. 2: Critical current (Ic) vs magnetic field (H) $T = 250mK$ for a type “A” junctions having $W = 20\mu m$ and $L = 250nm$ (left) and a type “B” junction with $W = 5\mu m$ and $L = 900nm$ (right) and Nb foils all of them placed in the measurement dewar and immersed in liquid $^4$He.

In all junctions, with normal conductor lengths $L$ typically ranging between 250nm and 1.1$\mu m$, we found a measurable supercurrent, see Fig.1 panels d-f. For type A structures, we measured the critical current in different junctions made on the same chip (the same transparency was assumed in this case). These junctions had different values of electrode gap (1.1$\mu m$ to 250nm) and consequently of barrier length. Data are consistent with an exponential decrease of $Ic$ vs. $L$ like in metallic SNS [17]. The Fraunhofer-like patterns shown in Fig.2 confirm the Josephson nature of the zero voltage current. The period measured for junctions of different widths and lengths is consistent with theoretical expectations, which take into account flux focusing effects [18]. The critical current was evaluated using a 1$\mu V$ criterion, while $R_N$ was determined from a linear fit of I-V curves at $V > 3mV$.

For short ($\Delta_S^{E_{th}} \rightarrow 0$) and tunnel junctions the only relevant energy scale is the gap of the superconductor $\Delta_S$ and at low temperatures $I_CR_N$ saturates at the value $\frac{1.326\pi \Delta_S}{2e}$. In the ideal case of SN interfaces with zero resistance and very long SNS junctions ($\Delta_S^{E_{th}} > 100$), $E_{th}$ determines both the value at which $I_CR_N$ saturates at $T \rightarrow 0$ and the characteristic temperature of its exponential decrease. In this limit $I_CR_N$ is not related to $\Delta_S$ but only to $E_{th}$ through the expression $I_CR_N = bE_{th}$, where $b = 10.52$. While the ratio $\frac{\Delta_S}{E_{th}}$ decreases, $b$ gets smaller. The complete $I_CR_N$ dependence on $\frac{\Delta_S}{E_{th}}$ is reported in Ref. 17. The proportionality between $I_CR_N$ and $E_{th}$ for very long junctions was experimentally demonstrated in the case of metallic SNS with transparent SN barriers [17]. For increasing SN interface resistance
TABLE I: \((I_C R_N)_{th}\) is a theoretical estimate made on the base of \(E_{th}^*\). Both \((I_C R_N)_{th}\) and \((I_C R_N)\) are taken at 250mK (see text).

| type | W [µm] | L [nm] | \(J_C\) [A/cm²] | \(E_{th}\) [µeV] | \(E_{th}^*\) [µeV] | \((I_C R_N)_{th}\) [mV] | \(I_C R_N\) [mV] | \((I_C R_N)_{th}/I_C R_N\) | \((T = 250\text{mK})\) |
|------|--------|-------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| J1   | A      | 20    | 250             | 2.68 × 10³     | 545            | 23             | 0.205          | 0.101          | 2.0            |
| J2   | A      | 20    | 800             | 4.35 × 10²     | 53             | 10             | 0.074          | 0.030          | 2.5            |
| J3   | B      | 10    | 800             | 1.18 × 10³     | 52             | 14             | 0.124          | 0.079          | 1.6            |
| J4   | B      | 5     | 900             | 8.96 × 10²     | 49             | 16             | 0.149          | 0.059          | 2.5            |
| J5   | C      | 0.45  | 400             | 2.84 × 10⁴     | 284            | 284            | 1.16           | 0.470          | 2.5            |
| J6   | C      | 0.4   | 800             | 5.05 × 10⁴     | 62             | 62             | 0.493          | 0.303          | 1.6            |

\(^a\)\(E_{th}^*\) has been taken equal to \(E_{th}\), see text.

Hammer et al. \[15\] showed that \(I_C\) vs \(T\) curves change their concavity from downward to upward and the energy scale of their temperature decay is determined by an effective Thouless energy \((E_{th}^*)\) which depends on the ratio \(r\) between the resistance of the SN interfaces and the resistance of the normal conductor. In ref. \[15\] is shown that for \(\Delta_S \to \infty\) and large \(r\) \((r > 10)\) the following approximate relation holds: \(E_{th}^*/E_{th} = Ar^B/(C + r)\), where \(A\), \(B\), and \(C\) are parameters which fit the numerical solutions and depend on \(\Delta_S / E_{th}^*\).

We introduce \(E_{th}^*\) in our discussion to have a single modeling parameter that has the only purpose to account for barrier properties. As the effective Thouless energy becomes smaller the value of \(I_C R_N\) at low temperatures also becomes smaller and the decrease of \(I_C\) at high temperatures faster. A reduced effective value of \(E_{th}\) also implies a larger value of the ratio \(\Delta_S / E_{th}^*\), in other words the junction gets longer as \(r\) increases. In our paper, in agreement with Ref. \[15\], we link the temperature decay of \(I_C\) to \(E_{th}^*\) and show that the latter value also determines the size of \(I_C R_N\) at low temperature.

In order to provide an estimate of \(E_{th}^*\) we measured \(I_C\) vs. \(T\) curves for all junctions. Three representative results (filled points) are shown in Fig.3. \(I_C(T)\) can be well approximated by an exponential function for sufficiently long junctions and high temperatures \((k_B T > 5E_{th})\): \(I_C(T) \propto \exp(-T/T^*)\) \[17\]. We have

\[17\]
used Eq. \( \text{I}_C \) to fit our data for all junctions of type A and B as shown in Fig. 3. The resulting values of \( E_{\text{th}}^* \) are reported in Table I. For these devices \( E_{\text{th}}^* \) is smaller than \( E_{\text{th}} \), which can be calculated from the relevant diffusion coefficients and junction lengths.

The values of the ratio \( \frac{\Delta_N b}{E_{\text{th}}^*} \) span from 60 to 170 and \( k_B T \gg E_{\text{th}}^* \) for all junctions in the temperature range considered in the fit (\( T \geq 500 \text{mK} \)), fully justifying the use of Eq. \( \text{I}_C \) \[17\]. Our analysis of \( I_C \) vs. \( T \) shows that type A and B junctions exhibit a behavior characteristic of much longer junctions with respect to their actual geometric length. \( I_C \) vs. \( T \) corresponding to junctions of type C is remarkably different from those of other devices as shown in Fig. 3. The curve is concave downward and saturates at 250mK. This curve shape is typical of junctions having SN interfaces with low barrier resistance (see Figure 6 in ref. \[15\].

FIG. 3: \( I_C \) vs \( T \) data points for junctions J2, J5, J3 (symbols) along with theoretical fit (dotted lines)
For these devices $T < E_{th}/k_B$ in the whole temperature range considered (low temperature regime) $^{15,17}$, $I_C(T)$ can be approximated by $I_C = (aE_{th}/eR_N)(1 - ce^{-aE_{th}/3.2k_BT})$ $^{17}$ ($R_N$ is 73.5Ω for J5). An excellent fit is achieved with an effective Thouless energy of $E^*_t = 284 \mu eV$ and parameters $a = 1.979$, $c = 1.45$. The quality of the fit, slightly deviating from the experimental data only for $T > 1.5K$, confirms that the value of $E^*_t$ is comparable to $E_{th}$ as opposed to cases A and B. This suggest that the nature and/or the geometry of super/semi interface characterizing type C can yield a higher effective Thouless energy.

The reasons for which Type C interfaces have better performance are not quite clear but are probably originated by a different structure following the peculiar fabrication procedure. This last includes Ti mask deposition, reactive ion etching, and mask removal by HF solution. In this configuration an etched wire of small width (450nm) is in contact with the superconductor not only on the top of the smooth mesa surface, like in cases A and B, but also through the two sides, at the rough surface of the etched side walls. It is however not possible to ascribe with certainty the improvement of the interface to the top contact, to the side contact or both. It is widely accepted that the relatively poor quality of S/N barriers is largely determined by reactive ion etching. Yet this is funded on data for junctions whose SN side contacts were taken on buried two dimensional electron gases $^{2,9}$. In those devices contacts were made to the side of active layers less than 10nm thick, which were charge populated by modulation doping. Our junctions are based on bulk doped surface layer and are therefore quite different from most systems studied in literature. Bulk doped structures like ours are more robust, as compared to modulation doped quantum wells, to the formation of a charge depleted (dead) layer at the two sides of the mesa after dry etching. We believe that the rough surface of the side walls (which is still perfectly conducting in our case) promotes the adhesion of metallic films thus improving effective contact area, and transparency. An inhomogeneous contact can present areas with different transparency: indeed the overall behavior of the junction is determined by those areas having a large transparency. Another mechanism worth future investigation is a possible change in the chemistry of the top surface in the epilayer due to deposition and subsequent removal of the Ti mask. A chemical reaction at the surface between the mask and the semiconductor could be favored, for instance, by local heating of the mask during the RIE.

In Tab. I we calculate theoretical expected $I_CR_N$ for J1-J6 after Ref. $^{17}$ on the basis of $E^*_t$. We find for all junctions, including J5 and J6, a factor that is around two between
theoretical and measured $I_C R_N$. This confirms the effectiveness of the model described in ref. [15]. Our data systematically show for the first time that SNS systems with non-ideal SN interfaces can be characterized by an energy scale ($E_{th}^*$) capable to account for barrier resistance and transport parameters simultaneously. The other interesting result is the identification of a fabrication process for which $E_{th}^*$ is almost equal to $E_{th}$ (J5 and J6). The agreement of $I_C R_N$ with existing theory is not perfect for both high transparency junctions (J5 and J6), and low transparency Junctions (J1-J4). A discrepancy with theory of the same order was also found in some works based on metallic SNS junctions [20, 21] and attributed to spurious factors like the effective area of the contact [17].

Finally we note that J5 and J6 exhibit an $I_C R_N$ value very close to the maximum obtainable for the given geometry and material parameters for ideally transparent interfaces. To the best of our knowledge similar results for semiconductor/superconductor devices were obtained only for junctions employing Si/Ge [22] and InAs nanowires [5]. We remark that, differently from the last two cited works, our devices are based on a standard top-down fabrication approach fully compliant with large scale integration. We stress that J5 and J6 were fabricated on different samples in different time. For J6 HF cleaning was more concentrated (1/20 instead of 1/50) and the normal conductor was ring shaped. To calculate the supercurrent density for J6 we considered $W$ as the sum of of the width of the two arms forming the ring. For the estimation of the Thouless energy we considered $L$ equal to one half the average circumference of the ring plus the gap between Nb electrodes and the ring. High values of the characteristic voltage have been obtained on similar structures produced with the same fabrication process. These are mostly SNS junctions having ring shaped normal conductor. Further details on SNS ring devices will be reported elsewhere.

In conclusion we showed that the quality of semi/super interface does play a crucial role in determining the value of the effective Thouless energy in SNS junctions. The comparison of different junction architectures shows that the reduction of $I_C R_N$ is accompanied/mediated by the reduction of effective Thouless energy. We determined a junction configuration maximizing $I_C R_N$ and supercurrent density. This opens the way to the realization of charge-controlled devices (J-dot) with critical currents larger than 10 nA.

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