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# Micro-SQUIDs based on $MgB_2$ nano-bridges for NEMS readout

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**Abstract**

We show the results obtained from the fabrication and characterisation of $MgB_2$ loops with two nano-bridges as superconducting weak links. These ring structures are made to operate as superconducting quantum interference devices and are investigated as readout system for cryogenics NEMS resonators. The nano-constrictions are fabricated by EBL and ion beam milling. The SQUIDs are characterised at different temperatures and measurements of the noise levels have been performed. The devices show high critical current densities and voltage modulations under applied magnetic field, close to the critical temperatures.

Keywords: SQUID, magnesium diboride, nano-bridges, NEMS

(Some figures may appear in colour only in the online journal)

## 1. Introduction

The relatively high superconducting critical temperature of magnesium diboride ($T_c = 39$ K) and its intermetallic properties makes $MgB_2$ a suitable material to fabricate superconductor quantum interference device (SQUID) [1]. For more than a decade, $MgB_2$ SQUIDs have been successfully fabricated and studied by several groups [2–7]. Nowadays, $MgB_2$-based SQUIDs are developed instruments for practical applications [8] and have been integrated into experimental systems, such as for magnetocardiography [9].

In recent years, a key development in SQUIDs has been the approach towards the nanoscale [10, 11]. Micro- and nano-SQUIDs could be used to measure various physical parameters in quantum metrology down to quantum limit [12]. In this field of study, a novel and very promising metrological application of micro-SQUIDs is to reading out nano-electromechanical system (NEMS) [13]. Because of the sizes of the moving parts of NEMS resonators, it is not practical to use a superconducting flux transformer as read out system at sub-micron level. Furthermore, stray inductances between the primary and secondary coils could reduce the coupling. Whereas, even if having an efficient direct coupling between NEMS resonator and micro-SQUID is critical, due to the shapes and the dimensions, nowadays this is the tendency [11, 13].

The key element of a SQUID is the Josephson junction. Dayem bridge technology applied to $MgB_2$ thin film provides a useful way to prepare Josephson junctions with a size of only a few tens of nanometres, ideal for micro-SQUID incorporation [14]. The long coherence length and the consequently high critical current density gives the advantage of easy manipulation of the junction barrier [11]. This was already demonstrated in nano-constriction on grained $MgB_2$ film with stable and reproducible technology [4, 6, 15], thus it is possible to use $MgB_2$ devices to readout NEMS. This new technology is promising over a wide spread of sectors from nanoscale metrology to many possible sensing applications. The aim is the use of the exquisite sensitivity of a SQUID-based readout that offers high flexibility to sense the displacement of a NEMS device through an inductive coupling

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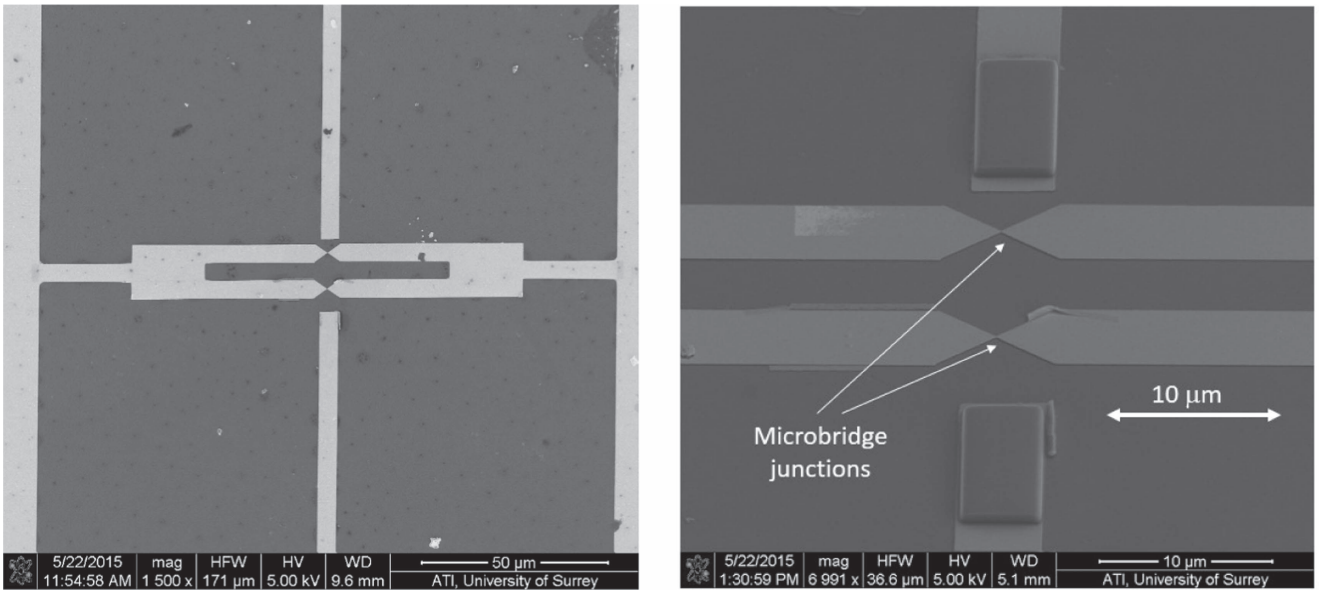


**Figure 1.** SEM images of the $MgB_2$ micro-SQUID with leads for NEMS resonator. On the left, an overview of the device D1; on the right, close image of the nano-bridges as Josephson junctions for device D2.

mechanism. The idea behind this work has the purpose of realising magnetometers, which allow optimised coupling between SQUID-readout and NEMS, combined with relatively high operating temperature. In order to reach this goal we fabricated micro-ring structured SQUIDS on very thin epitaxial films, while still maintaining good superconducting properties, and we reduced the constriction dimensions to less than 100 nm, like in [2–7]. The first technique will allow etching by using ion milling instead of focused ion beam, avoiding eventually Ga ion implantation. The second way, moving to nano-constrictions, will permit reduction of the geometric size of the ring-structure.

In this work we present the results of a first step for realising cryogenic SQUID-NEMS combinations. Two magnetometers, based on $MgB_2$ loop with two nano-constrictions were realised and characterised. The devices were fabricated by an electron beam lithography based approach starting from high quality very thin epitaxial films. Magnetometers properties were measured inside a pulse-tube cryocooler, able to access the temperature range from 2.5 to 40 K.

## 2. Experimental details

The SQUIDs are based on high quality $MgB_2$ thin films with thickness of 20 nm, grown by hybrid physical-chemical vapour deposition (HPCVD) on SiC substrates. The HPCVD method has been described in details elsewhere [16] and it allows the fabrication of superconducting magnesium diboride thin films with $T_c$ higher than the bulk value (40 K). In order to protect the superconducting layer from oxidation, a Cr/Au (5 nm/25 nm) layer has been deposited on it.

The coarse structure and the nano-constrictions have been defined by electron beam lithography using MAN2405 negative tone electron resist with a thickness of 500 nm. Then the geometry is transferred from the resist to the film by ion milling of the uncovered superconducting film. The final devices shown in figure 1 are constituted by a SQUID with two additional lateral leads, for subsequent attachment of the SiN microresonator on top of the superconducting loop. On the same $MgB_2$ thin film were fabricated two SQUIDs called D1 and D2. Figure 1 shows the two magnetometer loops with internal dimension of $65 \times 5\ \mu m^2$; at the centre of the loop there are the two nano-constrictions. D1 and D2 have nano-bridges of 63 nm wide and 55 nm wide, respectively (figure 2).

The SQUIDs have been characterised in a cryocooler with base temperature of 2.5 K. A pancake coil, of NbTi superconducting wire, fixed below the samples, allowed a magnetic field to be applied, so that the voltage modulation can be measured.

## 3. Results and discussion

Figure 3 shows the resistance versus temperature of the ring structures D1 and D2 measured with an excitation current of 5 $\mu$A. Both devices have a two-step transition: a step at higher temperature, close to the film $T_c$, due to SQUID arms and a step at lower temperature related to constrictions. Similar behaviour have been often observed after nano-structuration of $MgB_2$ film [6, 17]. The normal state resistance of device D1 is 17.5 $\Omega$ and the normal state resistance of device D2 is 27.5 $\Omega$.

In figure 4, typical examples of the measured SQUID current–voltage characteristics are shown for the two samples at several temperatures close to their respective $T_c$.

Figure 5 depicts the dependence on temperature of the measured critical current ($I_c$). The experimental data of $I_c$ was very well fitted by the formula [18] $I_c(T) = I_{c0}(1 - T/T_c)^{\alpha}$,

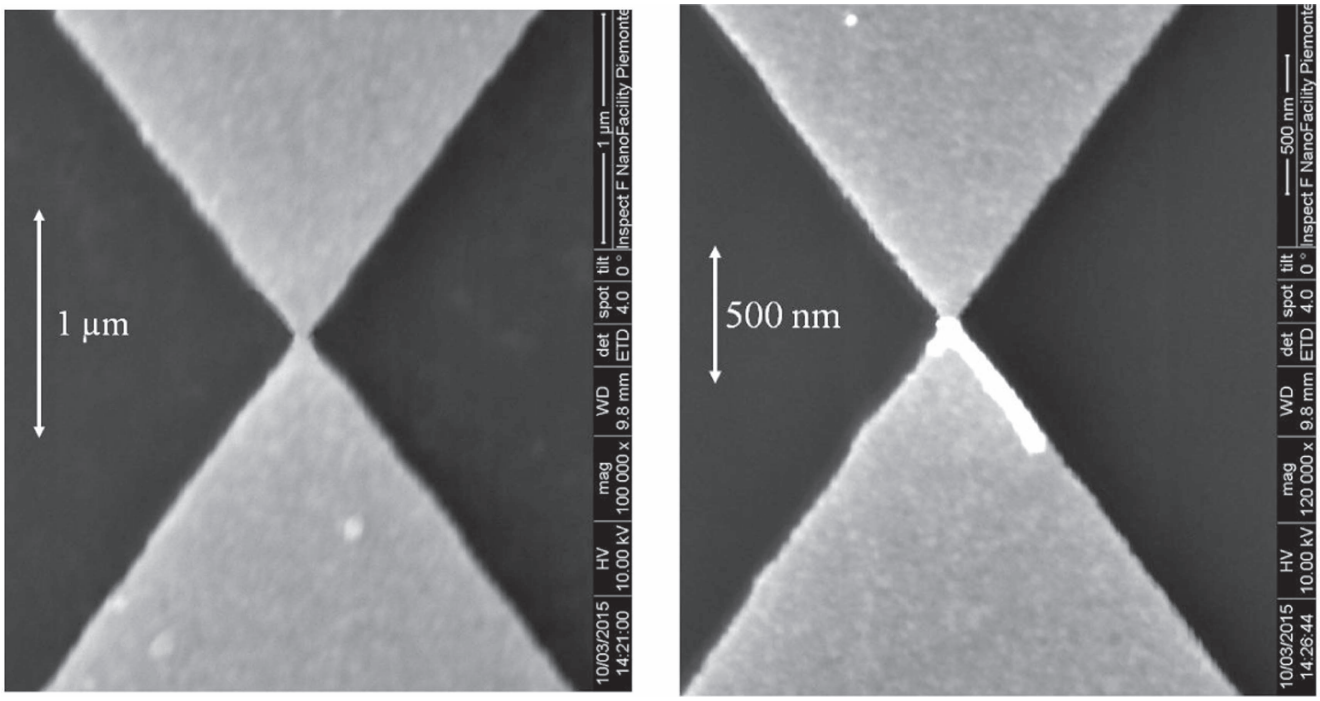


**Figure 2.** SEM images of the $MgB_2$ nano-constrictions. On the left, the nano-bridge (D1) is 63 nm wide. On the right, the nano-bridge (D2) is 55 nm wide.

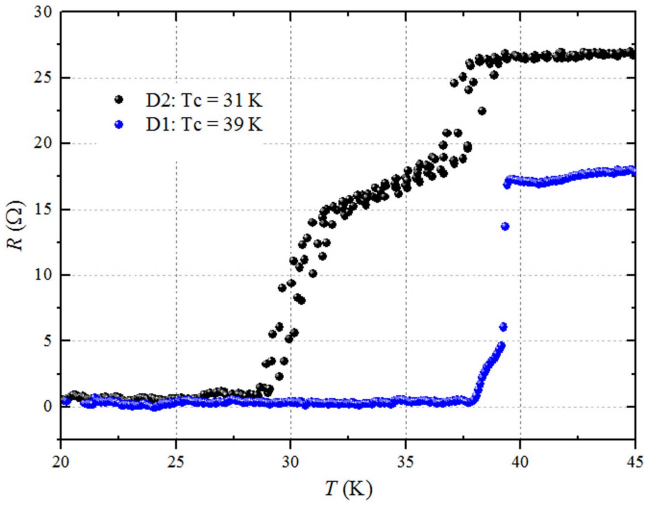


**Figure 3.** Critical temperatures of the two SQUIDs, measured by the four wire technique.

with $\alpha$ in the range between $1 \div 1.5$ for nano-bridges and between $2 \div 2.5$ for wide bridge. Taking $I_{c0}$, $T_c$ and $\alpha$ as free parameters in the fit procedure, we obtain critical temperature values close to those estimated by the four-wire technique, which indicates the goodness of the procedure. Whereas, $\alpha$ equals to 1.8 for D1 and 1.3 for D2 leads to behaviours similar to that of long nano-bridges with flux-flow-type [18] and of short nano-bridges based on high quality films [4].

By supposing these $I_c(T)$ behaviours still remain the same also down to lower temperatures, as measured in reference [19], it is possible to estimate the critical current of samples at 4.2 K, by extrapolating from the fits of $I_c$ versus $T$.

For the D1 device, $I_c(4.2\,\mathrm{K}) \approx 12.2\,\mathrm{mA}$ and, with a bridge cross section estimation of $A = 1.26 \times 10^{-11}\,\mathrm{cm}^2$, the critical current density results $J_c \approx 4.8 \times 10^8\,\mathrm{A\,cm}^{-2}$. Similarly for D2, with $I_c(4.2\,\mathrm{K}) \approx 0.8\,\mathrm{mA}$ and $A = 1.1 \times 10^{-11}\,\mathrm{cm}^2$, we calculate $J_c \approx 3.5 \times 10^7\,\mathrm{A\,cm}^{-2}$. The $J_c$ value of D2 sample results comparable to one obtained in references [4, 5], whereas the D1 device shows a higher current density value, like that reported in [20].

To observe the voltage modulation of the SQUID, the ring structure was biased at constant DC current above the critical current, while the voltage across the ring was monitored as a function of the applied magnetic field. Voltage modulation of the D1 sample has been observed up to 37 K. Figure 6 (left) shows modulations obtained at 36.5 K, biasing D1 SQUID in the range between 42.5 and 55 $\mu$A, where the largest modulation amplitude is about 3 $\mu$V, at 50 $\mu$A.

The effective SQUID area is estimated by the formula $A_{\mathrm{eff}} = \Phi_0/B_{\mathrm{ext}}$, where $\Phi_0 = 2.07 \times 10^{-15}\,\mathrm{T\,m}^2$ and $B_{\mathrm{ext}} = 7.742 \times 10^{-6}\,\mathrm{T}$ is the applied magnetic field needed to have one period of the voltage modulation. With these values, the effective D1 SQUID area result is $2.7 \times 10^{-10}\,\mathrm{m}^2$ (table 1). From the SEM image shown in figure 1, we estimate for the SQUID loop a length of 60 $\mu$m and a width of 4.5 $\mu$m, from wich the loop geometry area is about $2.98 \times 10^{-10}\,\mathrm{m}^2$. This value is very close to our measured effective area value, any difference probably arising from flux focusing effects due to the relatively wide SQUID loop track. We have measured the voltage as a function of magnetic field at different temperatures, in order to calculate the SQUID effective area as a function of the temperature $T$, as summarised in table 1. The results indicate that the SQUID effective area is essentially independent of temperature up to 37 K.

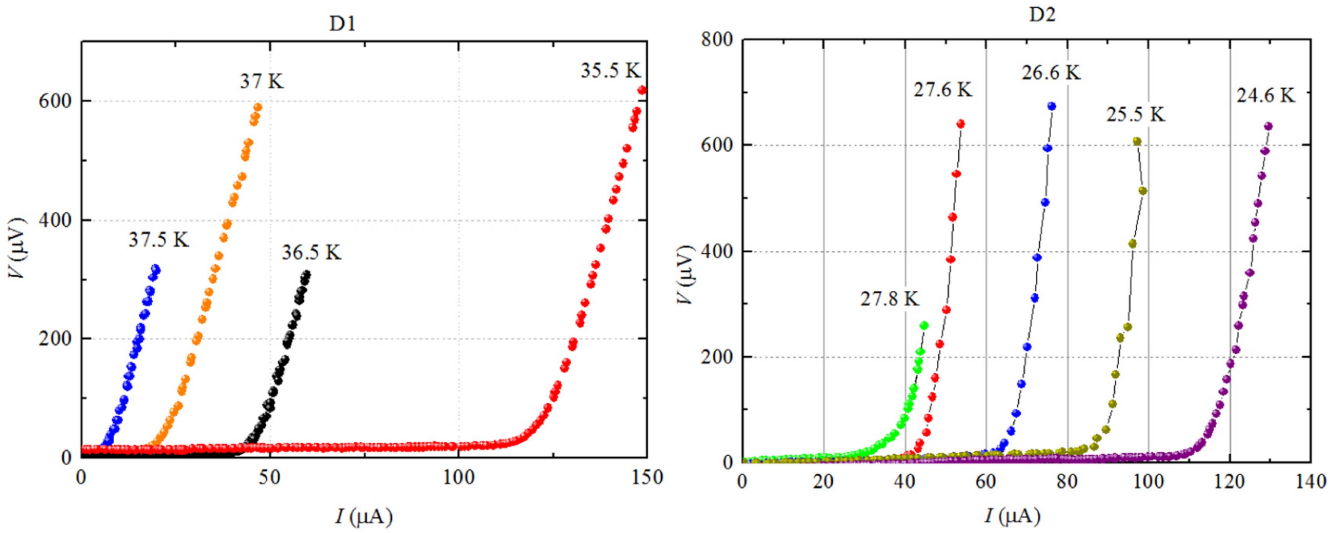


**Figure 4.** Current–Voltage characteristics of SQUID D1 (left) and D2 (right) in the range 35.5 K–37.5 K and 24.6 K–27.8 K, respectively.

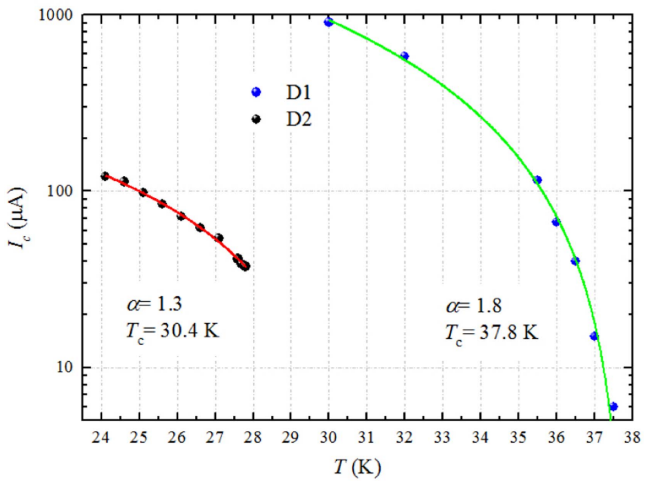


**Figure 5.** Critical currents of the D1 and D2 SQUID as a function of temperature (dots). The continuous lines show the theoretical fits.

As shown in figure 6 the amplitude of voltage modulation, (the peak-to-peak voltage $V_{p-p}$) depends on the bias current at a given temperature. Therefore, at a fixed temperature, we have measured some $V$–$\Phi$ curve at different bias current values, and calculated $V_{p-p}$ for each $V$–$\Phi$ plot. Among them, the largest $V_{p-p}$ value for this temperature has been selected (figure 6 right). By repeating this at different temperatures, the trend of $V_{p-p}$ as a function of temperature has been plotted in figure 7, showing that $V_{p-p}$ increases from 0.5 to 7 $\mu$V as the temperature changes from 37.5 to 30 K.

The noise spectrum of device D1 was determined under a bias current where the voltage modulation was maximum. A Stanford Research SR 560 voltage amplifier was used to amplify the SQUID output before recording the real-time voltage data and Fourier transforming it. A white noise level of 4.5 nV $Hz^{-1/2}$ is measured and below 10 Hz the noise magnitude is dominated by $1/f$ noise. At an operating temperature of 36.5 K we measured the flux to voltage transfer function $dV/d\Phi = 1.50 \times 10^{-5}$ V/ $\Phi_0$. Using the voltage white noise figure given above for the amplifier we can convert the white flux noise of this device to be $2.7 \times 10^{-4}$ $\Phi_0$ $Hz^{-1/2}$, a promising figure for such a high operating temperature, given the amplifier limitations. We believe the noise level across the frequency range above 10 Hz is dominated by the room temperature amplifier.

To improve on this we would need to increase the $V_{p-p}$ values in future work, either by making smaller junctions with higher resistance or by making sure the junction properties are matched. Another possibility is to use a low temperature amplifier such as SQUID Series Array Amplifier to improve the $MgB_2$ SQUID noise performance in future.

## 4. Conclusions

It is important for future SQUID-NEMS applications that the operating temperature of these combined exquisitely sensitive measurement devices should be at as high a temperature as is practical, in order to simplify operation and reduce complexity. $MgB_2$ ring structures have been investigated as new SQUID readout for NEMS technologies. With respect to previous $MgB_2$ devices [2, 3, 6–8], these superconducting micro-rings with Dayem nano-bridges have been fabricated on high quality very thin films (down to 20 nm) of epitaxial $MgB_2$ [4, 5]. The devices geometries were entirely fabricated by an electron beam lithography reducing the nano-bridges in the width range of 50–65 nm. At least one SQUID still shows voltage modulation as a function of the applied magnetic field up to 37 K. At 36.5 K, the voltage modulation was measured and the noise level of 4.5 nV $Hz^{-1/2}$ seems dominated by the room temperature amplifier. A SiN microresonator has been fabricated and will be positioned on top of the SQUID. These devices show also that is possible to further reduce the dimensions of ring structures (loop and constrictions) while still maintaining the SQUID behaviour.

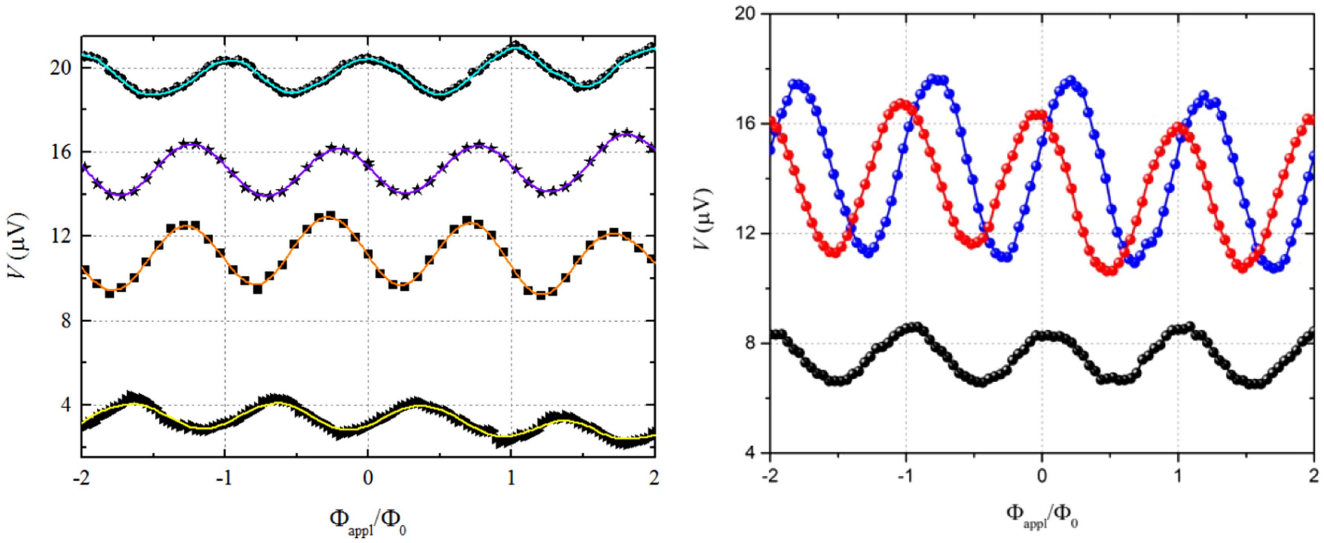


**Figure 6.** Voltage modulation of SQUID D1 versus applied magnetic field. On the left, at 36.5 K for different values of the bias current ranging between (from the bottom to the top) 42.5, 50, 53 and 55 $\mu$A. On the right, the three curves are measured at 37 K (black), 34 K (red) and 31 K (blue) respectively, each of them being with the largest $V_{p-p}$ at given temperature.

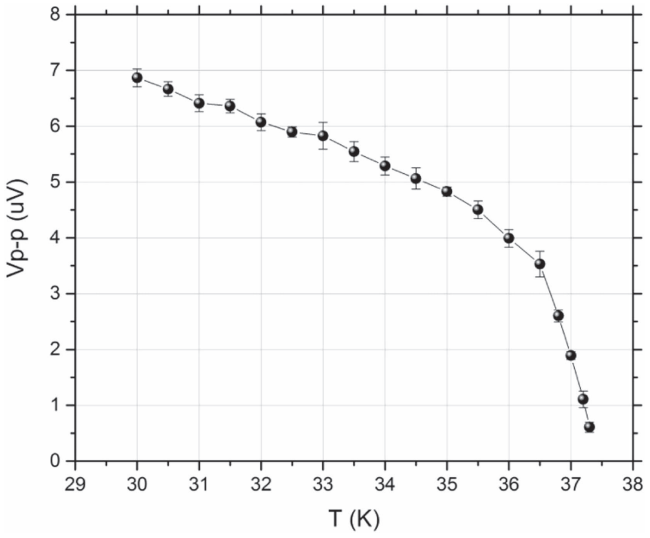


**Figure 7.** Voltage modulation peak-to-peak value $V_{p-p}$ of SQUID D1 as a function of the temperature.

**Table 1.** $MgB_2$ SQUID effective areas versus temperature for device D1.

| $T$(K) | $B_{ext}$ (T) | $A_{eff}$ ($m^2$) |
|---|---|---|
| 34.0 | $7.47 \times 10^{-6}$ | $2.77 \times 10^{-10}$ |
| 36.5 | $7.74 \times 10^{-6}$ | $2.67 \times 10^{-10}$ |
| 37.0 | $7.50 \times 10^{-6}$ | $2.75 \times 10^{-10}$ |

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