# Non-reciprocal Supercurrent in InSb Nanoflag-based Ballistic Josephson Junctions

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## 2D InSb *nanoflags* for quantum technologies

**Indium Antimonide** (InSb) is an extremely promising material in the field of quantum technologies, due to its very small effective mass, strong spin-orbit interaction (SOI) and giant effective g-factor. Thanks to that, it has gained much attention in the field of **unconventional superconductivity**.

Recently, many efforts have been made in the growth of a novel InSb 2D system - the nanoflag. These **free-standing**, **defect-free** zinc-blende structures are grown following the epitaxial approach largely used for nanowires. The 2D nature is crucial for design flexibility and broadens the range of applications.

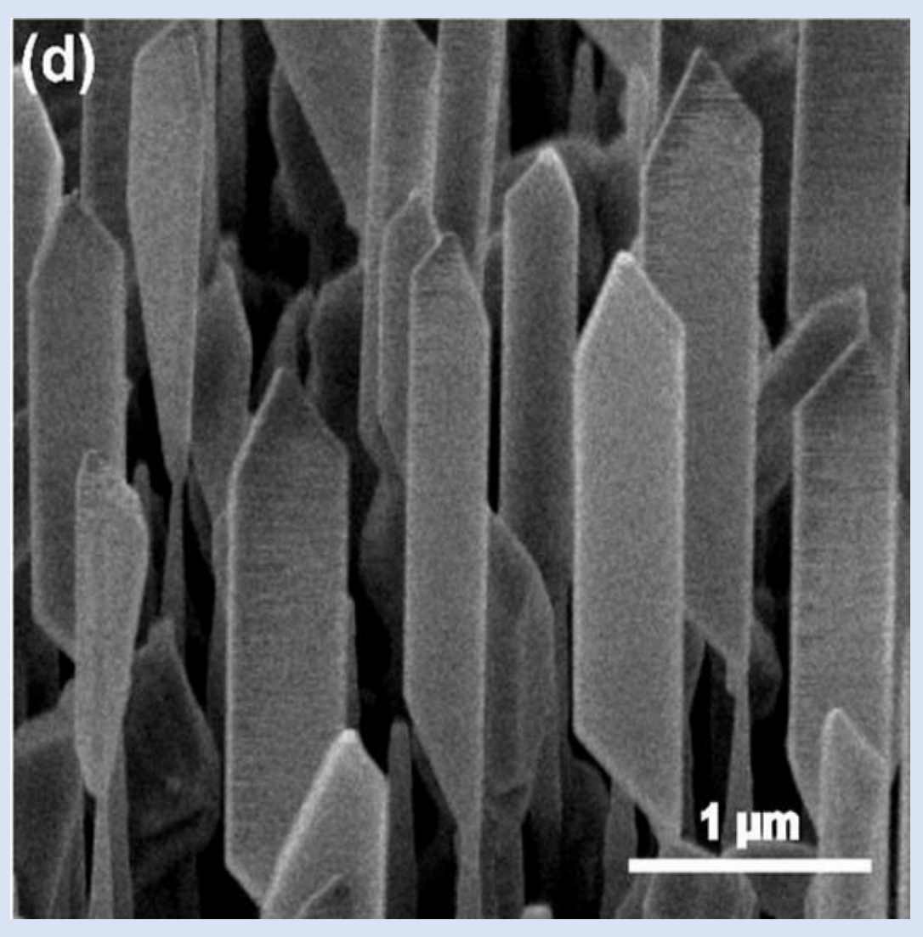

**Figure 1**: InSb nanoflags grown on InP nanowire stems, via Au-assisted CBE.

**Material parameters:**

- ☐ $m^* = 0.018 m_e$
- ☐ $E_{SOI} \sim 200\ \mu$eV
- ☐ $g^* \sim 50$

**Nanoflag dimensions:**

- ☐ Thickness $t \sim 100$ nm
- ☐ Width W $\sim 500$ nm
- ☐ Length $L \sim 2\ \mu m$

**I. Verma et al., *ACS Applied Nano Materials* 2021 *4* (6), 5825-5833**

## Observation of the Josephson diode effect

One of the most fascinating phenomena related to unconventional superconductivity is the **Supercurrent Diode Effect** (SDE), which was firstly reported in magnetic materials [1]. In practice, with accurate choice of the external parameters, the junction supports dissipation-less transport only in one direction, while it shows resistive behavior in the opposite. We show that these devices support SDE and Josephson effect at the same time, a scenario which is often referred to as **Josephson diode effect** (JDE).

The JDE in this system is driven by an **in-plane magnetic field** $B_{ip}$, which simultaneously breaks the **time-reversal** and **inversion symmetry**, thanks to the strong SOI.

We observe that the positive and negative switching currents are different when $B_{ip} \neq 0$. The polarity of the asymmetry in the switching current ($\Delta I_{sw} \equiv I_{sw}^+ - I_{sw}^-$) depends on the relative angle $\theta$ between the current flow in the junction and the direction of $\vec{B}_{ip}$.

Indeed, changing the sign of the product $\vec{B}_{ip} \times \vec{I}_{sd}$ , the polarity is inverted. In both cases, $\Delta I_{sw}$ has a maximum at $B_{ip} \sim \pm 10$ mT and it is completely suppressed above $|B_{ip}| \sim 20$ mT.

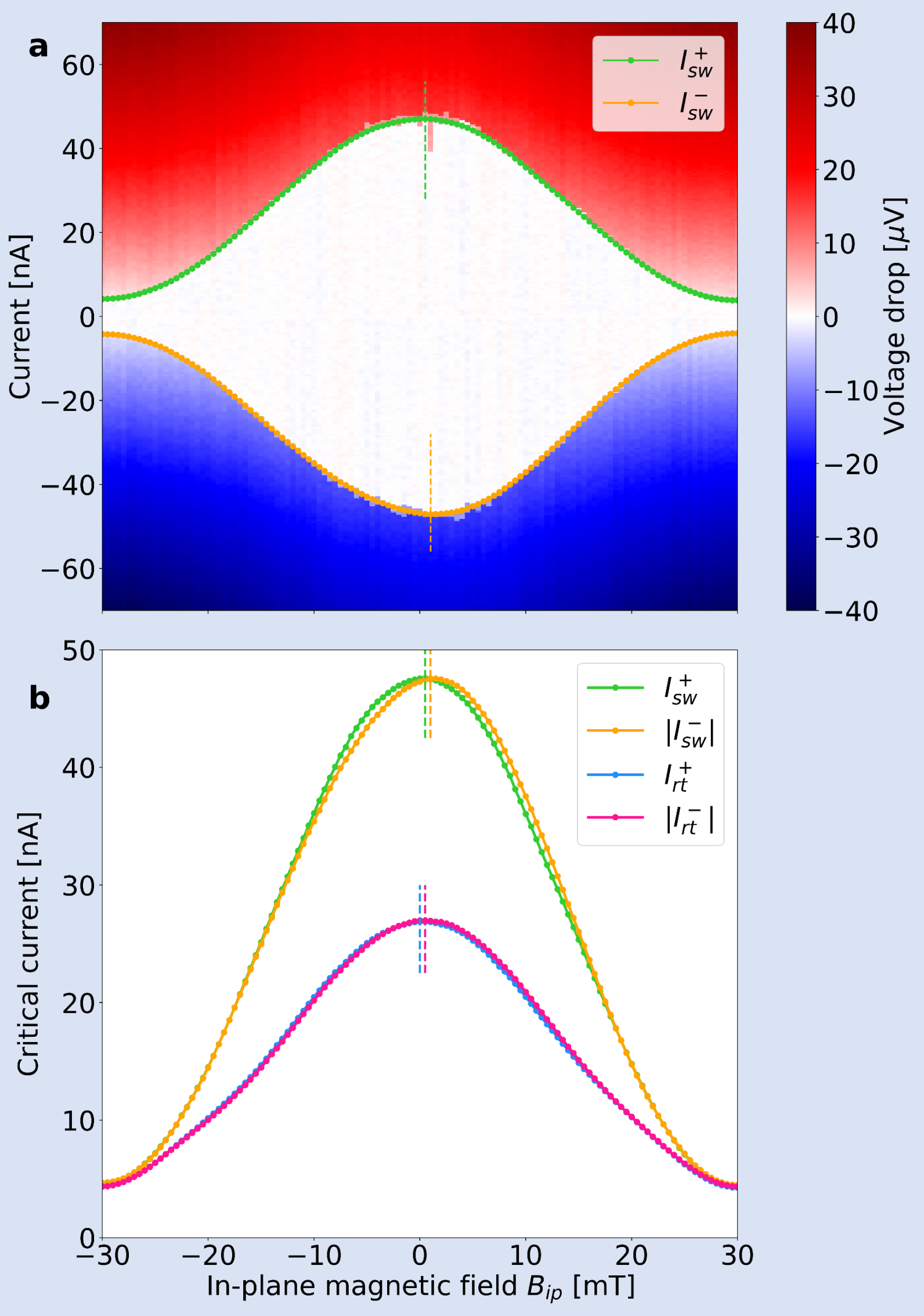

**Figure 4**: Interference pattern in presence of $B_{ip}$. $I_{sw}^+$ and $I_{sw}^-$ have different values for $B_{ip} \neq 0$. The point of maximum of the positive (negative) branch is highlighted with the green (orange) line. In Fig b, the absolute values are reported, also for the retrapping currents. Device G5.

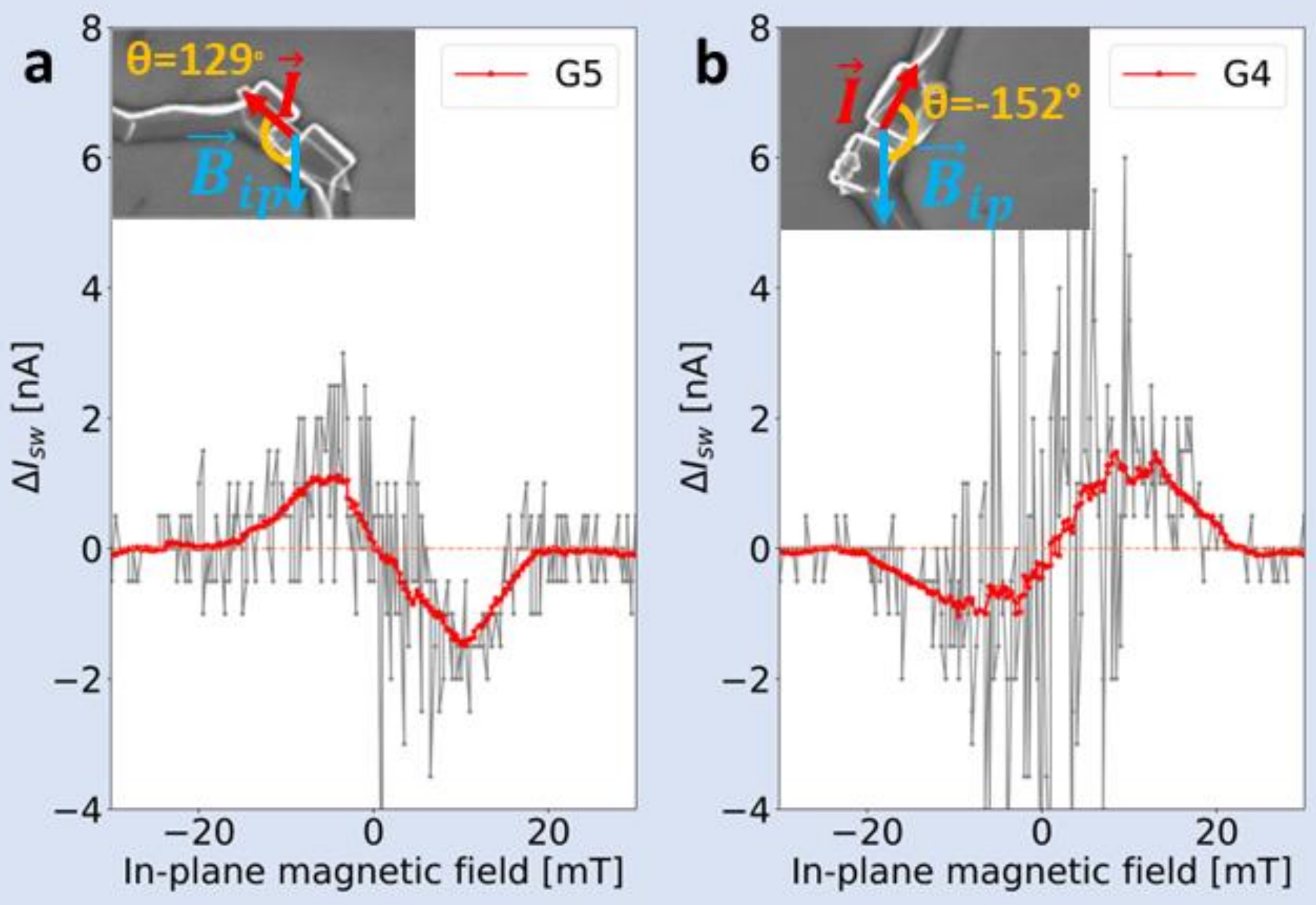

**Figure 5:** Asymmetry in $I_{sw}$with respect to $B_{ip}$, for two different relative orientations between the current flow and the magnetic field direction, as indicated in the insets. In both cases, the asymmetry grows linearly for small field, while it decreases to zero at high field. The maximum effect is found at $B_{ip} \sim$ ±10 mT, while the asymmetry is smoothly suppressed at field higher than $B_{ip} \sim$ ±20 mT. The polarity is reversed, accordingly with the difference sign of $\theta$. T = 30 mK and $V_{bg}$= 40 V.

[1]: F. Ando et al., *Nature* volume 584, pages 373–376 (2020)

## Ballistic superconductivity in InSb Josephson junctions

We have studied the nanoflag-based devices with low-temperature **magneto-transport** measurements.
With the deposition of Niobium (Nb) contacts, we have realized planar hybrid devices which show **dissipation-less transport**. The electron mean free path $\lambda_{MFP}$is larger than the normal region length L, so that the device works in ballistic regime. This superconducting-normal-superconducting (SNS) junctions support the flow of supercurrent up to $I_c \sim 50$ nA. Moreover, the devices act as a **Josephson FET**, i.e., the critical current is tunable via field effect, with a voltage gate ($V_{bg}$).

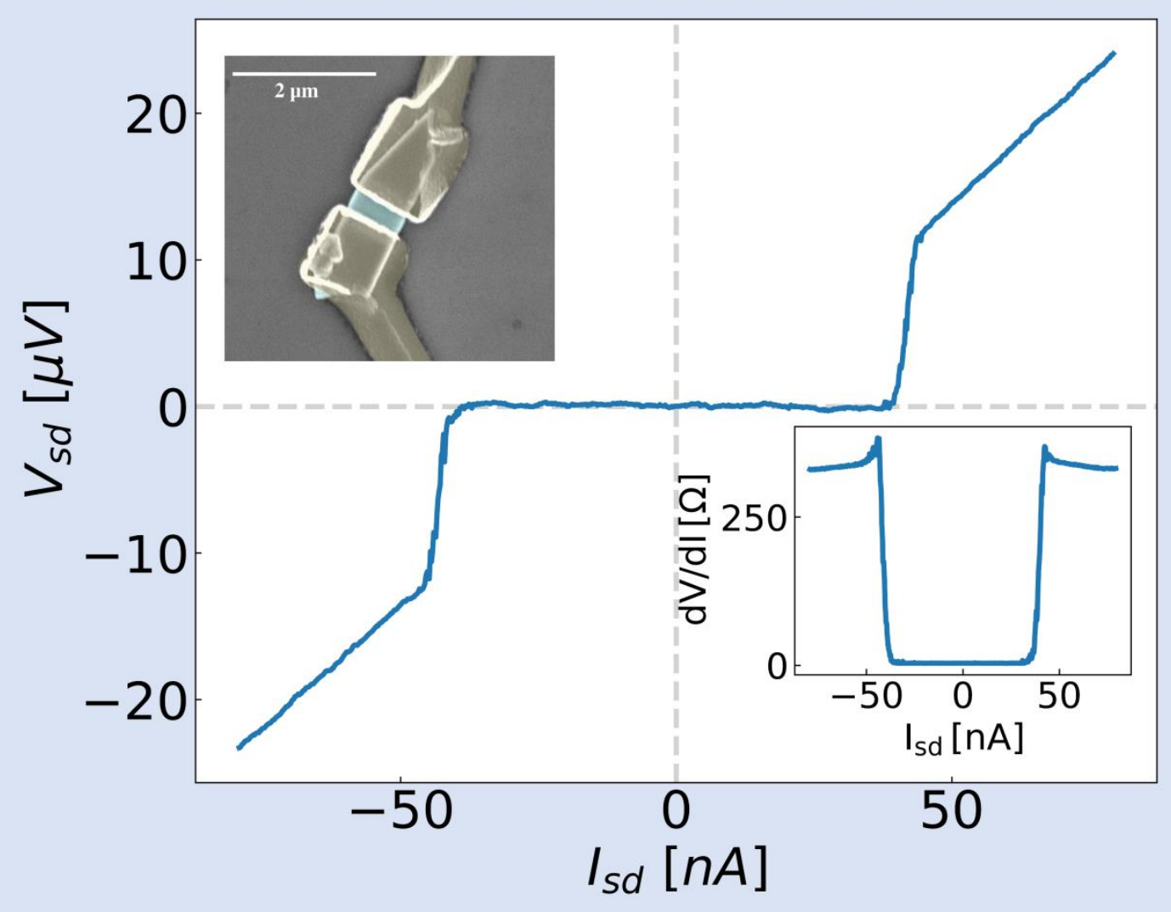

**Figure 2:** IV characteristics, measured at T=250 mK. Top-left inset: SEM image of one device.
Bottom-right inset: differential resistance as function of the bias current. We clearly distinguish the superconducting region, where dissipation-less transport occurs.

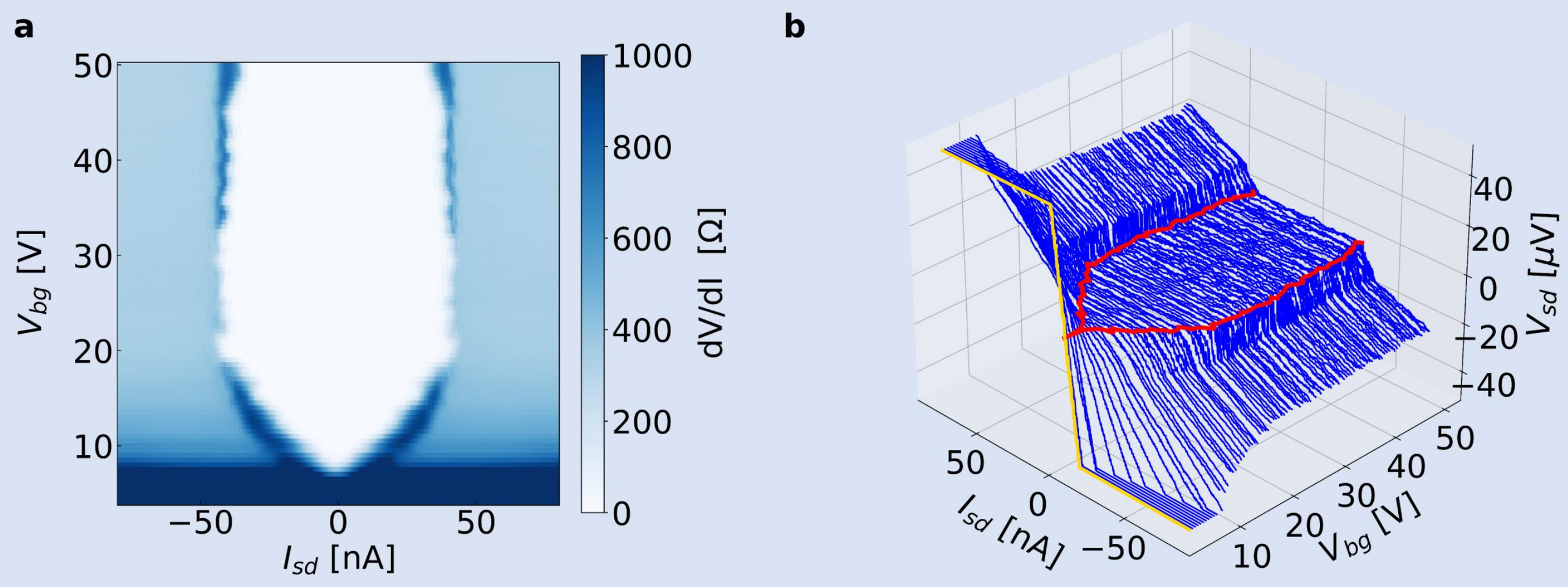

**Figure 3:** Color-scale plot of differential resistance dV/dI as a function of the current bias $I_{sd}$ and back gate voltage $V_{bg}$. (b) 3D plot shows the trend of simultaneously measured DC $V - I$ curves at different back gate voltages. The first curve (at lowest back gate voltage) is highlighted in yellow. Red lines indicate the transition between the superconductive and the dissipative regime. The supercurrent increases with increasing the back gate voltage above pinch off. $T = 250$ mK.

Due to the high tunability of the device and to the complex mechanisms at play, the InSb-based Josephson junction is an ideal playground to look for signatures of topological superconductivity, as the presence of $4\pi$-periodic Andreev bound states.

**S. Salimian et al., *Applied Physics Letters* 119, 214004 (2021)**

## Tunability of the Josephson diode effect

We can exploit this effect to get insight on the relevant transport mechanisms at play in InSb nanoflags. By remapping the experimental data with respect to $B_{ip,\perp}$, we have observed that the trend of $\Delta I_{sw}$ is the same for each measured orientation, while the magnitude depends on $\theta$. For symmetry reasons [2], this implies that the **Rashba SOI** is dominant in these systems.

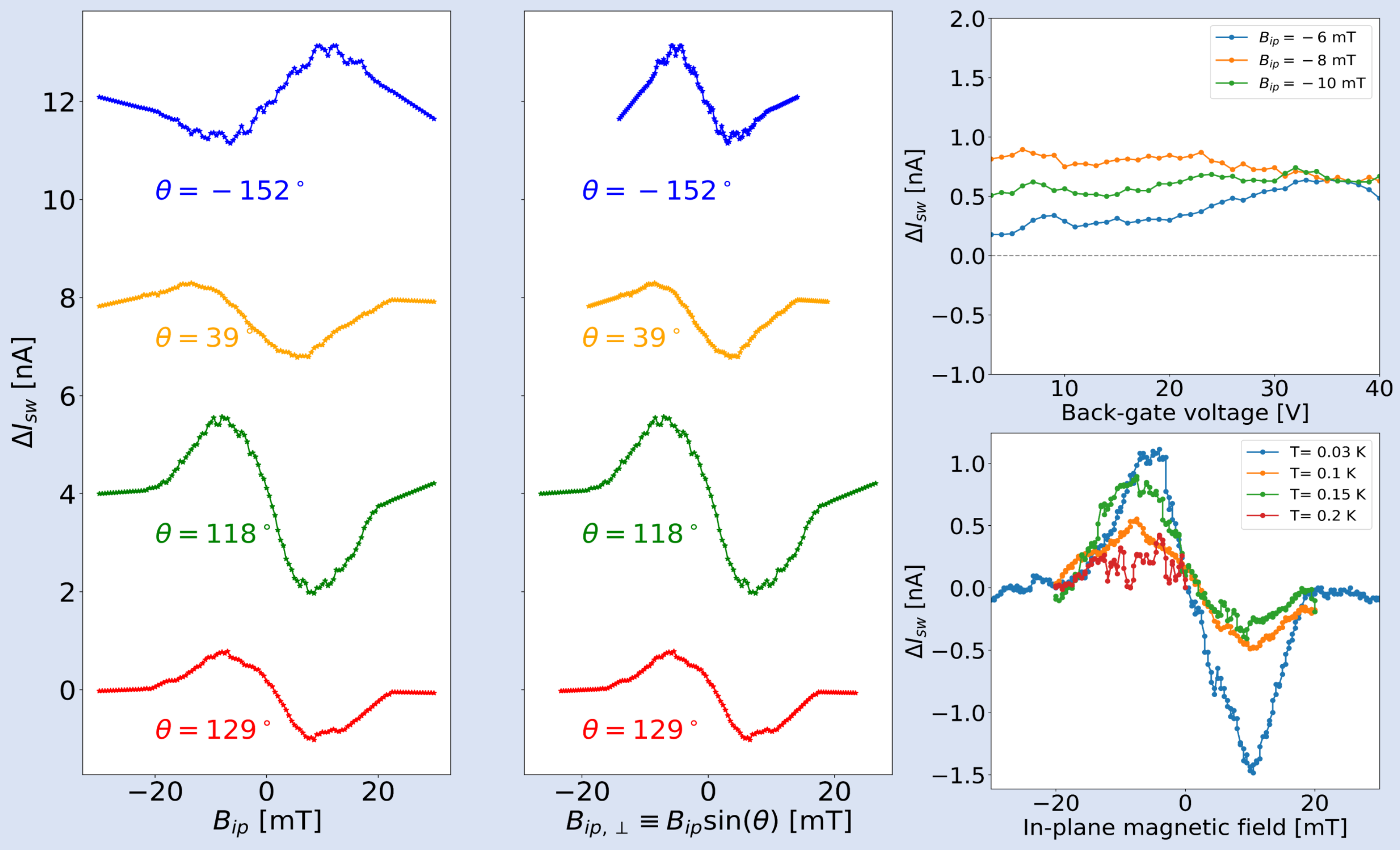

**Figure 6:** Behavior of the JDE with in-plane magnetic field, perpendicular component of the in-plane field, back–gate voltage, and temperature. (a) Asymmetry versus in-plane field for different orientations of the devices. (b) Asymmetry versus the component of the magnetic field perpendicular to the current flow. The amplitude of the effect is reduced for angles approaching θ = ±nπ. (c) Asymmetry versus back–gate voltage, for three different values of the applied in–plane magnetic field. (d) Temperature–dependence of the asymmetry.

We have also studied the dependence of the JDE on back-gate voltage and temperature. In the first case, we have observed that, for finite values of $B_{ip}$, there is no change in $\Delta I_{sw}$ for varying $V_{bg}$. On the other side, the temperature $(T)$ strongly suppresses the effect, which is completely smeared out for $T \gtrsim 200$ mK. This is related to the different trend in temperature of the **higher harmonics** included in the current-phase relation (CPR). Since the JDE is only present when the CPR is non-monochromatic, we have observed the quenching of $\Delta I_{sw}$ for values of T where the switching current itself is only smoothly modified with respect to the value at base T (30 mK).

[2]: A. Rasmussen et al, *Physical Review B* 93, 155406 (2016)
[3]: C. Baumgartner et al, *Nature Nanotechnology* volume 17, pages 39–44 (2022)