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Delfanazari, K., Ma, P., Puddy, R.K. et al. (8 more authors) (2019) Andreev reflections and magnetotransport in 2D Josephson junctions. In: Journal of Physics: Conference Series. 13th Workshop on Low Temperature Electronics, WOLTE-13, 10-13 Sep 2018, Sorrento, Italy. IOP Publishing .

<https://doi.org/10.1088/1742-6596/1182/1/012010>

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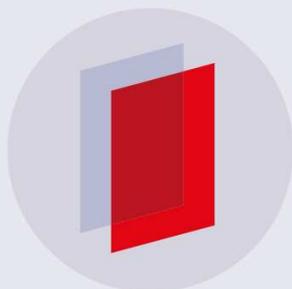
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To cite this article: Kaveh Delfanazari *et al* 2019 *J. Phys.: Conf. Ser.* **1182** 012010

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Andreev reflections and magnetotransport in 2D Josephson junctions

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Abstract. In this paper, the subharmonic energy gap structures (SGS) and induced superconductivity, due to multiple Andreev reflections, in indium gallium arsenide ($\text{In}_{0.75}\text{Ga}_{0.25}\text{As}$) two-dimensional electron gas (2DEG) are discussed at different temperatures and magnetic fields. Strong suppression of both SGS and induced gap are observed as a function of temperature and magnetic field. The differential conductance of the Josephson junctions (JJs) as a function of external in-plane magnetic fields shows an asymmetric response to positive and negative magnetic field sweeps with a conductance maximum at close to zero. Our approach to quantum transport studies of the ballistic 2D JJs may open a new road towards scalable and integrated quantum processing and help pave the way for the development of topological circuits for the realization of the next generation of quantum processors.

1. Introduction

Electronic and photonic devices based on Josephson junction (JJ) as a fundamental quantum phenomenon [1] have received much attention in quantum science and technology [2-19]. The combination of superconductors with semiconductors and formation of hybrid superconducting-semiconducting-superconducting (S-Sm-S) JJ offers a broad range of applications especially in the growing field of topological quantum processing and computing. For instance, topological phases of matter which potentially contain Majorana fermions, exotic particles that are their own antiparticles, has recently been observed at the interface of semiconducting wires [20,21], and at the interface of semiconducting two-dimensional electron gas [22,23], in contact to a s-wave superconductor. Such platforms have been proposed to be the building blocks of the next generation of quantum computers and they have the capability of revolutionising the way the information is processed, transferred and stored. However, to achieve (and protect) the topological phases (from excitations) in such system one



needs to make a homogeneous and barrier-free contacts between the superconductor and semiconductor. The formation of highly transparent interfaces in hybrid JJs as well as scaling up the number of JJs in a single chip to realise a quantum device applicable for real-world quantum technology are challenging to attain in many material platforms [24]. In searching for a promising platform, our in-house molecular beam epitaxy (MBE) grown $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}/\text{In}_{0.75}\text{Al}_{0.25}\text{As}/\text{GaAs}$ two-dimensional electron gas (2DEG) offers low electron effective mass, large g -factor and strong Rashba spin-orbit coupling [25-28]. These features make $\text{In}_{0.75}\text{Al}_{0.25}\text{As}$ a very attractive material in the field of quantum computing, electronics, spintronics and photonics. In addition to all these advantages, the ability to tune the indium composition allows the formation of highly transmissive S-Sm interfaces. The wafer can also be grown in a relatively large dimension, allowing fabrication of a few hundreds of hybrid JJs on a superconducting circuit so overcoming the scalability challenging of the quantum devices [26].

In this paper, the quantum transport measurements for two hybrid JJs made from Nb superconducting leads in contact with $\text{In}_{0.75}\text{Al}_{0.25}\text{As}$ 2DEG are demonstrated as a function of temperature and in-plane magnetic field. The 2DEG in the heterostructure was formed 120 nm below the wafer surface. Shubnikov–de Haas oscillations and Hall effect measurements are performed at temperature $T=1.5$ K to obtain electron density $n_s=2.24\times 10^{11}$ (cm^{-2}) and mobility $\mu_e=2.5\times 10^5$ (cm^2/Vs).

Each junction was measured individually using a two-terminal lock-in measurement technique. The measurements were carried out in a dilution fridge with a base temperature of 40 mK in a magnetic field of up to 9 T. We observe induced superconducting properties into the 2DEG at low source-drain voltage V_{SD} bias due to multiple Andreev reflections at the boundary of the materials and Andreev bound states at the Nb- $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}$ interfaces. The subharmonic energy gap structures (SGS) [26-29] are observed when the applied V_{SD} satisfies the expression $V = 2\Delta/ne$, where the Δ is the Nb superconducting gap energy, e is the electron charge and n is an integer. It was found that both induced superconducting gap and SGS are strongly temperature and magnetic field dependent. We find that the differential conductance of the JJs as a function of external in-plane magnetic fields shows an asymmetric dI/dV curve for positive and negative magnetic fields with a conductance maximum at close to zero.

2. Andreev reflections in hybrid superconductor/two-dimensional electron gas/superconductor Josephson junctions

At low temperatures, at the interface of the superconductor-semiconductor S-Sm contact (in the case of our devices, at the Nb- $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}$ interfaces), there are two possible reflection mechanisms: (i) normal reflection (specular quasiparticle reflection) in which there will be no charge transmission through the interface and (ii) the Andreev reflections, in which the incoming electron (hole) will be reflected as a hole (electron) in the opposite spin subband and transfer a $2e$ charge into superconducting leads. As the superconducting condensate consists of spin singlet Cooper pairs, the reflected hole has the opposite spin as the incoming electron. The best model that describes such S-Sm system is known as the Blonder–Tinkham–Klapwijk (BTK) model [29].

The influence of the superconductor order parameter in 2DEG results in the nonlinear differential conductance observation in the system [26]. If the interface is not transparent enough, a zero-bias peak within the gap will be formed. This is because part of the incident electrons will be normal reflected and there will be competition between the Andreev and normal reflections. This process will also result in the increase of the resistance in the system. However, if a highly transparent- transmission $T^1 = (1 + Z^2)^{-1} = 1$ or barrier strength $Z=0$ - interface was formed between two superconducting and semiconducting materials, in this case all incident electrons undergo Andreev reflection and an excess current I_{exc} flows through the system because of electron- and hole-like quasiparticles correlations below transition temperature of the junction. This process results in the reduction of the differential resistance within the energy gap Δ/e and therefore a flat U-shape dip in the dV/dI (V_{SD}) is expected to be observed (see Fig. 1 for different base temperatures).

According to BTK model, no tunnelling barrier is formed at the S-Sm interfaces in our JJs therefore an estimate of $Z < 0.2$ or $T > 0.96$ was made. Due to the formation of highly transparent interface between Nb and $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}$ in our JJs, and therefore due to perfect multiple Andreev reflections at the interface, an induced gap Δ_{ind} of around $100 \mu\text{eV}$ is measured in the 2DEG [26,27]. The subharmonic energy gap structures (SGS) are also observed when the applied V_{SD} satisfies the expression $V = 2\Delta/ne$, where the Δ is the Nb superconducting gap energy, $n = 1, 2, 3, \dots$ is an integer, and e is the electron charge. As shown in Fig. 1, the observed induced gap and SGS structures (dashed arrows) are strongly temperature dependent which suppress significantly at temperatures above 400 mK.

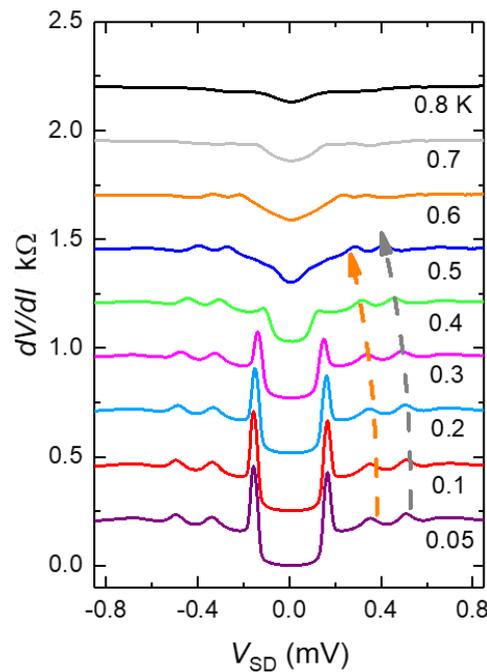


Figure 1. **Multiple Andreev reflections and subharmonic gap structures in superconducting $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}$ two-dimensional electron gas:** Temperature dependence induced superconductivity in 2DEG as a function of source-drain voltage V_{SD} . The pronounced SGS peaks due to multiple Andreev reflections in dV/dI (V_{SD}) shift towards zero voltage bias when the base temperature is increased. The grey and orange dashed lines indicate the temperature evolution of the SGS.

3. Magnetotransport in hybrid superconductor/two-dimensional electron gas/superconductor Josephson junctions

Figure 2 (a) shows the colour coded plot of dV/dI as a function of voltage V and perpendicular magnetic field B and at $T = 50 \text{ mK}$. The induced gap and SGS are clearly seen. It can be seen that the induced gap and SGS features that are evidences of multiple Andreev reflections are both suppressed, the position of the peaks shift toward zero bias and their amplitudes diminish with further increasing of the applied field. The Fraunhofer-like oscillations of I_c at low fields $0 < B \text{ (mT)} < 5$ can also be seen in Fig. 2(a). In our JJs the oscillation of supercurrent differs from the Fraunhofer pattern because the devices are designed purposely for mass production: the length of each JJ is 850 nm at the shortest path which increases to $26 \mu\text{m}$ at the end of the active region so dephasing from the normal 2DEG regions either side of the junction reduces the junction's area considerably [26,27].

Figure 2(b) shows the magnetotransport of one Nb- $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}$ -Nb JJ. The dI/dV (B) shows an

increase with a maximum at close to zero B as magnetic field is swept from positive to negative fields. When the field polarity is changed from positive to negative, there will be a decrease in differential conductance, but the curve does not follow the trends of the positive fields so an asymmetric magnetotransport curve is observed for fields $-0.3 < B$ (mT) < 0.3 . This effect has been discussed in detail elsewhere [27,30].

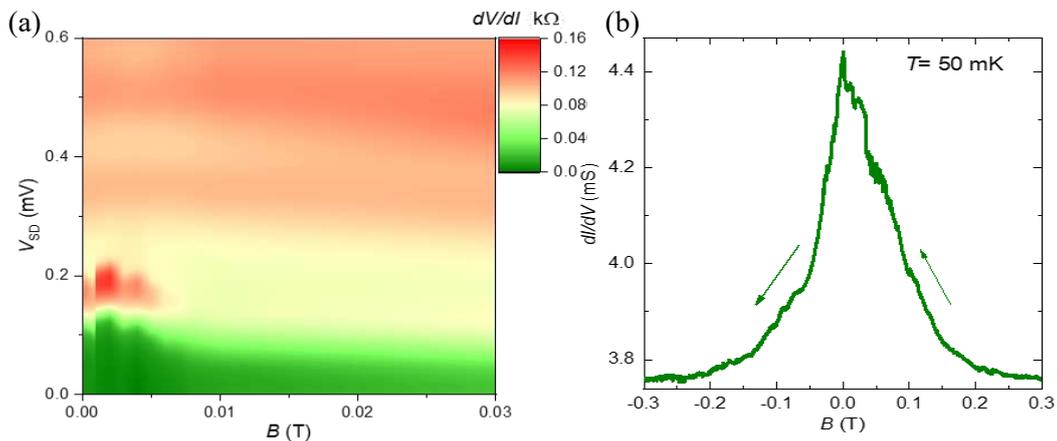


Figure 2: **Magnetotransport in superconducting $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}$ two-dimensional electron gas:** (a) the induced superconductivity in 2DEG and SGS as a function of source-drain voltage V_{SD} and applied magnetic field. The pronounced SGS peaks due to multiple Andreev reflections in dV/dI (V_{SD}, B) shift towards zero bias when the magnetic field is increased. (b) The differential conductance (dI/dV) vs. applied in-plane magnetic field at source-drain voltage $V_{\text{SD}} = 0$ and temperature $T = 50$ mK. Sweep directions are shown by arrows.

4. Conclusion

We demonstrated 2D Josephson junctions based on hybrid superconducting Nb/ $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}$ two-dimensional electron gas platform and discussed the induced superconductivity and subharmonic gap structures as a result of multiple Andreev reflections at the interface of two materials. The quantum transport measurements were carried out at different temperatures and magnetic fields. Strong suppression of Andreev reflection was found when the temperature and magnetic field were increased. An asymmetric magnetotransport curve with a conductance maximum at close to zero field was measured as a result of JJ response to positive and negative magnetic fields. Our approach may open a new road towards scalable and integrated quantum processing and help pave the way for the development of topological quantum integrated circuits for the realization of the next generation of quantum processors.

Acknowledgments

The authors acknowledge financial support from EPSRC.

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