TRANSPORT AND SUPERCONDUCTING PROPERTIES OF A NEAR-SURFACE INAS TWO-DIMENSIONAL ELECTRON GAS

Ph.D. Thesis booklet

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1 Introduction

Superconducting electronic circuits and qubit architectures are among the fastest-growing areas in physics, where significant advancements have been made over the last few years [1]. Today, multiple quantum computers exist across different countries, with the quantity of qubits, their core building blocks, reaching up to a thousand. While it is necessary to increase the number of qubits, it is just as important, if not more, to increase their quality. Currently, one of the most serious challenges in this field is the limited lifetime of qubit states, as they are prone to information loss via decoherence and relaxation by environmental interactions.

One promising approach to address this issue is the development of novel superconductor-semiconductor hybrid devices. Here we can combine the unique properties of superconductors with the gate tunability of semiconductors, enabling innovative qubit implementations like gatemons [2, 3, 4, 5, 6, 7], gatemonium [8] or Andreev qubits [9, 10, 11, 12]. It is proposed that topological protection of the qubits is possible using materials with strong spin-orbit coupling (SOC) in combination with superconductors, thus extending their lifetime manyfold [13, 14, 15, 16, 17, 18, 19]. Despite extensive efforts to realize this through Majorana-based qubits in semiconductor nanowires and two-dimensional electron gases (2DEGs), conclusive evidence has not yet been produced. Similarly, while recent works achieved new milestones in Kitaev chains based on quantum dot-superconductor arrays, further improvements are needed [20, 21, 22, 23, 24].

A central component of these architectures is a superconductor-normal-superconductor junction, or Josephson junction, wherein the normal region, created from a semiconductor, Andreev bound states can form. These states carry the supercurrent through the junction, and due to their unique dispersion relations, which can be used as a basis for a qubit realisation, they are the focal point of multiple research routes. The properties of these states are highly investigated using multiple methods from the deployment of tunnel probes [25, 26, 27, 28, 29, 30, 31, 32], through microwave spectroscopy [33, 34, 35, 36, 37, 38] to superconducting current-phase measurements [39, 40, 41, 42, 43, 44, 45].

Near-surface two-dimensional electron gases combined with an epitaxially grown superconducting layer have all of the properties required when searching for an ideal platform to realise quantum bits. They possess a relatively high mobility, strong SOC, while also maintaining a high-quality superconductor-semiconductor interface due to the closeness of the 2DEG layer to the surface of the semiconductor [46, 47, 48]. These systems are promising candidates for realising devices for quantum computing [5, 49, 50, 51], and thus gathered strong interest over the last few years.

Among the most commonly used semiconductors for creating quantum wells is indium arsenide (InAS), which has proven its potential, in the form of a nanowire, to realise Majorana-based devices [52]. However, the limited scalability of nanowires poses a significant challenge after the initial characterization. To overcome this, the focus has shifted toward InAs-based 2DEGs, which allow more flexibility in both device geometry and scalability, while keeping the excellent properties of the InAs nanowires [17, 18]. Early works using InAs 2DEGs employed either a gallium antimonide (GaSb) or indium phosphide (InP) wafer as the basis for the heterostructure [53, 54, 55]. Compared to GaSb, InP is more preferable from a technological point of view. However, gallium arsenide (GaAs) is similarly suitable, as it is both less expensive and more resistive, the latter of which is important in high-frequency measurements, making it superior in quantum computing applications, where both the manipulation and readout of qubits occur in the GHz regime.

2 Objectives

My work focused on fabricating devices using a novel GaAs-based near-surface InAs 2DEG and evaluating its suitability in quantum computing applications. This included everything from basic transport characterization of the platform to studying superconductor-semiconductor hybrid devices. Given that similar platforms have only been studied for under a decade [46, 56], no one in our research group had any prior experience with them. Consequently, I had to adapt a fabrication process for other systems and optimize it, then provide feedback on the quality of the material based on different measurements (scanning/tunneling electron microscopy, transport measurements), which helped to finalize the growth process. This included the testing of the heterostructure resistance to the etching of the epitaxial Al layer, as it was reported previously to have a negative effect [56].

My general goal was to establish this platform as a potential host for single-channel Andreev bound states. Controlling the number of conductance channels can be achieved in a quantum point contact (QPC) [57], therefore, my first objective was to create one on this platform and realize conductance quantization. For this, ballistic transport is required; therefore, the 2DEG must possess a suitably large mean free path. This can be verified using low-temperature magnetoresistance measurements at low field, from which we can estimate the mobility and mean free path of the 2DEG. Studying the heterostructure at larger magnetic field, from the temperature dependence of the Shubnikov-de Haas oscillation, it is possible to gain information about the disorder potential of the system as well as the effective mass of its charge carriers [58, 59, 60]. With sufficiently high mean free path in the range of a few 100 nm, we can realize a QPC, in which conductance quantization can be achieved.

In addition to a good quality 2DEG, quantum computing applications demand the presence of a superconductor with a highly transparent interface. In this project, this was achieved by an epitaxially grown aluminium (Al) layer. To validate both the quality of the Al layer and the transparency of the interface, my second main objective was to create Josephson junctions, where, through the observation of multiple Andreev reflections, we can estimate the induced gap of the 2DEG. The combination of the Josephson junction with a QPC would be the first step towards the realization of Andreev bound states in the single-channel limit.

Another way to probe the properties of the Andreev bound state is through the use of high-frequency measurements. My third goal was to fabricate superconducting resonators coupled to Radio Frequency Superconducting Quantum Interference Devices (RF SQUIDs) using the epitaxial Al layer of the heterostructure. Through the resonance frequency, one can observe the magnetic field modulation of the critical current inside the Josephson junction of the RF SQUID, and directly estimate the transmission of the Josephson junction.

Thesis points

T1 I studied GaAs-based near-surface InAs 2DEG structures using magnetoresistance measurements in the 1.5-50 K range. After ensuring single-subband conduction in the bare wafer, I have estimated the mobility ($\mu \approx 10^5\,\mathrm{cm^2/Vs}$) and mean-free path ($l_m \approx 1\,\mathrm{\mu m}$) of the 2DEG. These values were not affected by the etching of the epitaxial Al layer. By analysing Shubnikov-de Haas oscillations, I determined the Dingle temperature, from which I calculated the elastic scattering time, which was approximately 20 times lower than the transport lifetime. I fabricated devices with a dielectric and top gate, and I found a consistently reduced mobility from $(8-13)\cdot 10^4\,\mathrm{cm^2/Vs}$ to $(2-4)\cdot 10^4\,\mathrm{cm^2/Vs}$ and an increased Dingle temperature from 17-28 K to 38-50 K, indicating an increase in backscattering and disorder. Lastly, I fabricated and measured devices with quantum point contacts and realized quantized conductance up to $G = 8\,e^2/h$. By using DC bias spectroscopy in the quantum Hall regime, I determined the g-factor, $|g_\perp| = 15.8$.

T2 I have fabricated multiple near-surface InAs 2DEG samples containing Josephson junctions using an epitaxial Al layer as a superconductor, then studied them in the mK regime. In non-gated devices of 0.5 µm length and 4 µm width, I observed a critical current over 0.15 µA, while in a gated junction with a length of 0.3 µm and a width of 9 µm, I measured a gate-tunable critical current up to 1.5 µA. Using the multiple Andreev reflections, I estimated the induced gap in the InAs 2DEG to be Δ^*=125 µeV. Superconducting interference measurements showed a Fraunhofer pattern, indicating a homogeneous sample. Based on its periodicity, the effective junction length was significantly increased, which I attribute to a µm-scale Pearl length. When combining a Josephson junction with a QPC, I was able to measure a finite critical current even in the few-channel regime. Here, I observed a Gaussian shape in the superconducting interference measurements, demonstrating that in a QPC, the spatial current distribution is altered.

T3 I have fabricated superconducting resonators from the epitaxial Al layer of a near-surface InAs 2DEG, then coupled them to an RF SQUID using the InAs 2DEG as a weak link. I observed the periodic modulation of the resonance frequency as a function of magnetic flux in mK temperatures. The current-phase relation of the Josephson junction could be determined, from which the average transparency of the Andreev bound states was estimated to reach up to $\tau = 0.72$. Using an out-of-plane magnetic field, we performed supercurrent interference measurements and obtained a Fraunhofer pattern utilizing the envelope function of the resonance frequency. An in-plane magnetic field resulted in the direction-dependent asymmetry of the Fraunhofer pattern. In all devices, we estimated an internal quality factor of $Q_i \approx 1000$, an order of magnitude smaller than the value measured on control samples without an RF SQUID and a dielectric cover layer.

List of publications

T1-2: Máté Sütő, Tamás Prok, Péter Makk, Magdhi Kirti, Giorgio Biasiol, Szabolcs Csonka, and Endre Tóvári. Near-surface InAs two-dimensional electron gas on a GaAs substrate: Characterization and superconducting proximity effect. Phys. Rev. B, 106:235404, Dec 2022.

T1-2: Maghdi Kirti, **Máté Sütő**, Endre Tóvári, Péter Makk, Tamás Prok, Szabolcs Csonka, Pritam Banerjee, Piu Rajak, Regina Ciancio, Jasper R. Plaisier, Pietro Parisse and Giorgio Biasiol. Optimization of In-Situ Growth of Superconducting Al/InAs Hybrid Systems on GaAs for the Development of Quantum Electronic Circuits. Materials 2025, 18, 385.

T3: Zoltán Scherübl, **Máté Sütő**, Dávid Kóti, Endre Tóvári, Csaba Horváth, Tamás Kalmár, Bence Vasas, Martin Berke, Magdhi Kirti, Giorgio Biasiol, Szabolcs Csonka, Péter Makk, and Gergő Fülöp. Determination of the current-phase relation of an InAs 2DEG Josephson junction with a microwave resonator. Phys. Rev. Res., 7:023173, May 2025.

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