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# Analysis of charge transport in a tunnel junction based on magnetic insulator $CrCl_3$

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**Abstract.** This paper investigates charge transport in tunnel junctions based on the two-dimensional magnetic insulator chromium trichloride ($CrCl_3$). The tunneling device, consisting of a 9 nm thick $CrCl_3$ flake sandwiched between graphite contacts, exhibited two distinct tunneling mechanisms: direct tunneling at low voltages and Fowler – Nordheim tunneling at high voltages. At low temperatures, tunneling was suppressed by antiparallel spin alignment in $CrCl_3$ layers, while at high temperatures above 18 K the effective tunnel barrier height decreased and sharp current increase was observed. An unusual increase in the barrier height was observed in the temperature range of 20–23 K. Obtained results highlight the enhanced spin filtering effects in thicker $CrCl_3$-based tunnel junctions, providing insights for spintronic applications.

**Keywords:** tunnel junction, magnetic insulator, chromium trichloride, antiferromagnetism, charge transport

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# Анализ зарядового транспорта в туннельном переходе на основе магнитного изолятора $CrCl_3$

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**Аннотация.** В данной статье исследуется зарядовый транспорт в туннельных переходах на основе двумерного магнитного изолятора – хлорида хрома ($CrCl_3$). Туннельное устройство, состоящее из $CrCl_3$ толщиной 9 нм, находящегося между двух графитовых контактов, продемонстрировало два различных механизма туннелирования: прямое туннелирование при низких напряжениях и туннелирование Фаулера – Нордгейма при высоких напряжениях. При низких температурах туннелирование подавлялось из-за антипараллельного выравнивания спинов в слоях $CrCl_3$, в то время как при высоких температурах выше 18 K эффективная высота туннельного барьера уменьшалась и наблюдалось резкое увеличение тока. Необычное увеличение высоты барьера наблюдалось в диапазоне температур 20—23 K. Полученные результаты свидетельствуют об усилении эффектов спиновой фильтрации в туннельных переходах на основе слоев $CrCl_3$ относительно большой толщины, что может быть востребовано в спинтронных приложениях.

**Ключевые слова:** туннельный переход, магнитный изолятор, хлорид хрома, антиферромагнетизм, зарядовый транспорт

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## Introduction

Tunnel junctions are foundational components in modern spintronic devices, where the interplay between charge and spin transport underpins their functionality [1, 2]. Such devices typically consist of two conductive electrodes separated by an insulating barrier, enabling charge carriers to traverse the barrier via quantum tunneling. The tunneling process, while fundamentally quantum mechanical, can be significantly influenced by the magnetic and electronic properties of the insulating layer, paving the way for novel functionalities in spin-dependent transport [1].

In this context, the emergence of two-dimensional magnetic insulators [3, 4], such as chromium trichloride ($CrCl_3$), offers exciting possibilities for engineering tunnel junctions with unique spintronic properties. $CrCl_3$ is particularly compelling due to its antiferromagnetic ordering with in-plane magnetization and small anisotropy [5, 6]. As a member of the van der Waals materials family, it exhibits strong in-plane bonding and weak interlayer interactions, enabling precise control over its thickness and properties through exfoliation or other fabrication techniques. Furthermore, its magnetic insulating nature makes it an ideal candidate for mediating spin-dependent tunneling, with potential applications in spin filters, magnetic memory [4], and quantum information technologies [3].

Despite its promising characteristics, a comprehensive understanding of charge transport in tunnel junctions based on $CrCl_3$ remains partially incomplete. Most studies concentrate on relatively thin layers of $CrCl_3$ with small surface areas, enabling the exploration of how specific properties depend on the number of layers [7]. Here, we examine the transport characteristics of a tunnel junction with a relatively large thickness of approximately 9 nm (14 layers of $CrCl_3$) and a large surface area of about 100 $\mu m^2$. We explore how the transport regime depends on the applied voltage and temperature, demonstrating that spin filtering effects and their suppression with temperature could be significantly more pronounced in these thicker magnetic tunnel junctions.

## Materials and Methods

An optical microscope image of the device under study is shown in Fig. 1, *a*.

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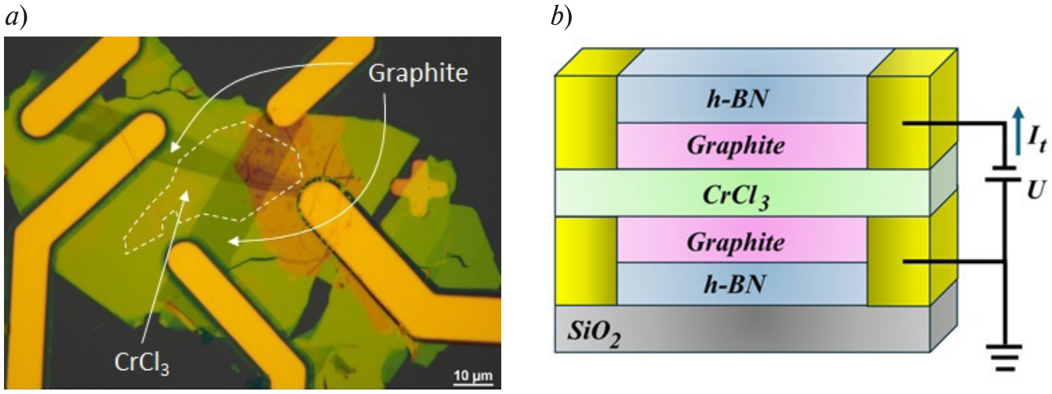

Fig. 1. Optical microscope image of the device (*a*); the dashed white line marks the $CrCl_3$ flake. Schematic of the device (*b*)

First, a separate flake of $CrCl_3$ was exfoliated from the bulk crystal by a scotch tape method. Next, employing the dry transfer technique [2], a stack was fabricated on a $Si/SiO_2$ substrate, comprising the $CrCl_3$ flake sandwiched between two thin graphite contacts and encapsulated within two hexagonal boron nitride (h-BN) layers, as illustrated in Fig. 1, *b*. The stacking was carried out in an inert gas atmosphere in the glovebox to prevent possible degradation of the materials. The thickness of the layers was estimated by optical contrast and was 9 nm for the $CrCl_3$ flake, 4 nm for the graphite contacts, and about 30 nm for the h-BN layers. Top and bottom graphite layers were contacted with V/Au metal electrodes (4 nm/40 nm) prefabricated by standard electron beam lithography on $SiO_2/Si$ substrate near the exfoliated bottom h-BN layer.

The current-voltage characteristics of the device were studied in the Physical Property Measurement System (Quantum Design) in the temperature range of 2–23 K. The tunneling current $I$ was measured as a function of applied voltage $U$ by a lock-in technique using SR830 amplifier (Stanford Research Systems).

## Results and Discussion

Fig. 2, *a* shows the current-voltage, $I(U)$, characteristic of the fabricated tunnel junction device measured at $T = 2$ K.

At low voltages, a linear dependence is clearly observed, which is characteristic of the direct electron tunneling through the dielectric layer. At voltages above 3 V, the current increases exponentially, which can be explained by tunneling in the field emission regime according to the Fowler – Nordheim (FN) mechanism, which is described by the formula:

$$I \propto U^2 e^{\left(-\frac{4d\sqrt{2m^*\Phi^3}}{3\hbar eU}\right)}, \qquad (1)$$

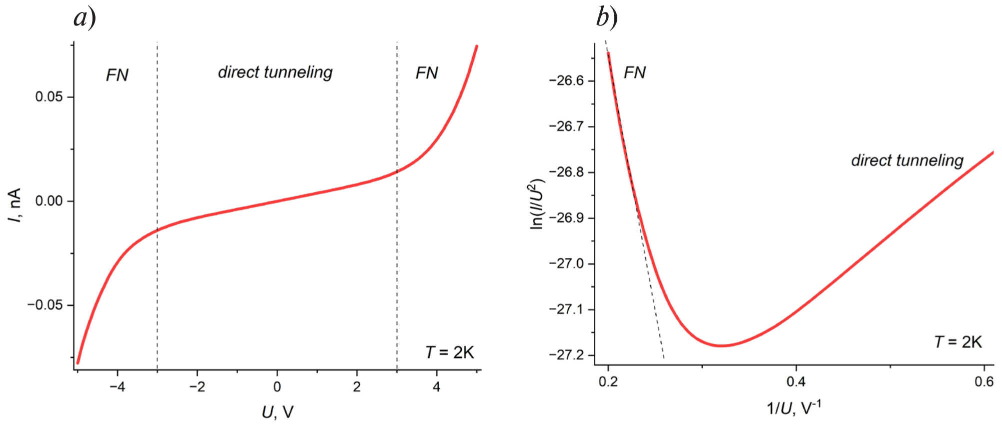

Fig. 2. Current-voltage curve of the device measured at $T = 2$ K (*a*). The same curve plotted in Fowler – Nordheim coordinates. The dashed line represents a linear fit at high voltages (*b*)

where Φ is the barrier height at zero applied voltage, $d$ is the thickness of the dielectric layer, $m^*$ is the electron effective mass, $\hbar$ is the reduced Planck constant, $e$ is the electron charge.

In the $\ln(I/U^2)$ vs. $1/U$ coordinates the current-voltage characteristic has a linear form at high voltages (Fig. 2, *b*), which confirms the FN transport mechanism. From the slope of the linear dependence, the barrier height Φ can be estimated using the FN formula (1). Assuming that the effective mass is equal to the free-electron mass, the linear fit of the experimental data (shown by the dashed line in Fig. 2, *b*) gives $\Phi = 0.32$ eV at 2 K.

Fig. 3, *a* shows a two-dimensional map of the tunneling current as a function of voltage and temperature.

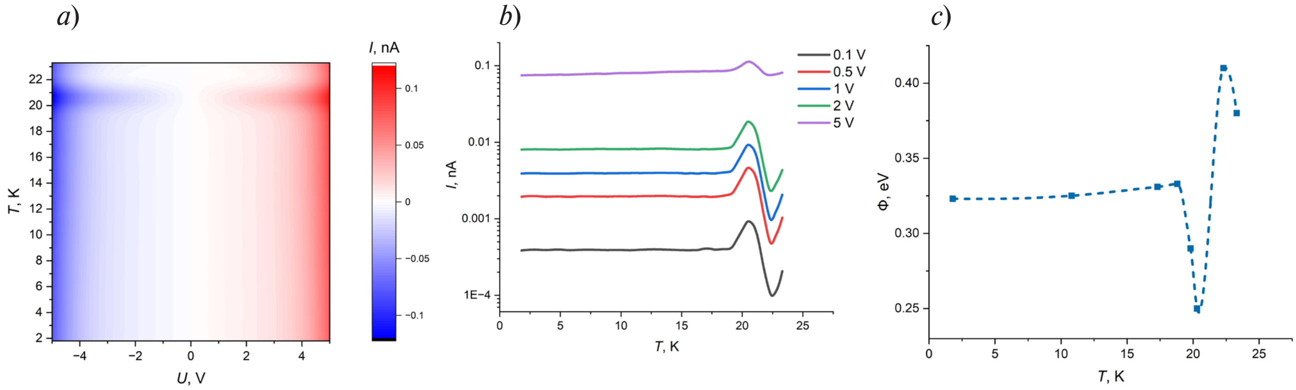

Fig. 3. Current dependence on temperature and voltage (*a*). Current-temperature curves at different voltages (*b*). Dependence of barrier height on temperature (*c*)

The cross-sections of this map at fixed voltage values are presented in Fig. 3, *b*. In the 2–18 K range the current depends weakly on temperature. Above 18 K a sharp increase in current is observed with a maximum at 20.5 K. In the 20–23 K range the current decreases significantly and a local minimum is observed at 22.5 K.

By fitting the current-voltage curves obtained at different temperatures using the FN formula (1), the dependence of the barrier height $\Phi(T)$ was calculated as shown in Fig. 3, *c*. It is evident that at about 20 K a sharp decrease in the barrier height is observed from 0.33 to 0.25 eV, while at 22.5 K the barrier height increases up to 0.41 eV.

In the experiments with thinner $CrCl_3$ samples, the $I(T)$ dependence usually shows a much weaker (no more than a few percent) local current maximum at $T = 17$ K, which is explained by the destruction of the antiferromagnetic phase [5]. In contrast, in our case, we observe a sharp increase in current by more than 100% (at low voltages) at approximately the same temperature in the region of 18–20 K. This can be explained by the fact that with an increase in the tunnel barrier thickness the spin filtration efficiency increases [6]. Moreover, this effect could be more pronounced due to the relatively large surface area of the used tunnel junction [8].

Thus, at low temperatures, tunneling is hindered because the electron spins are antiparallel in adjacent layers of the $CrCl_3$ crystal. When the antiferromagnetic state is disrupted above 18 K this effect weakens sharply, and a significant reduction in the effective barrier height is observed together with corresponding increase in the tunneling current. The further notable increase in barrier height in the range of 20–23 K is not typical, and the physical mechanism behind this behavior is not yet clear. In the near future, we plan to conduct transport experiments in a magnetic field, which will help to clarify the possible mechanism responsible for the observed behavior.

## Conclusion

In this study, we investigated the charge transport characteristics of a tunnel junction based on $CrCl_3$ with a relatively large thickness and surface area. We identified two distinct transport regimes: (i) direct tunneling at low voltages, characterized by a linear current-voltage relationship, and (ii) FN tunneling at higher voltages, exhibiting an exponential current-voltage characteristic. Using the FN formula, we estimated the effective barrier height to be about 0.32 eV at 2 K. At temperatures above 18 K, a significant reduction in barrier height and an increase in tunneling current are observed, which can be attributed to the disruption of the antiferromagnetic state in the $CrCl_3$ crystal. However, an unusual increase in barrier height observed at temperatures above 20 K remains unexplained. Future experiments, particularly in magnetic fields, are expected to shed light on the underlying mechanisms governing these transport behaviors, offering valuable insights for the development of spintronic devices.

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