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The Influence of a Magnetic Field on Advanced Silicon Diode Thermometers at Low Temperature Range

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An urgent task of modern extreme electronics is the creation of interchangeable high-precision miniature silicon diode thermometers capable of reliably operating at low and ultra-low temperatures under the influence of strong magnetic fields. Such thermometers are in demand for scientific and technical projects related to diagnosing the operation of blocks of superconducting magnetic systems necessary for the creation of thermonuclear fusion installations - the main source of energy in the future, as well as scientific experiments in the Large Hadron Collider. At the same time, it is known that the most popular commercial cryogenic silicon diode thermometers (SiDTs) are not recommended for use in environments exposed to strong magnetic fields at temperatures below 60 K.

We have developed a new generation of advanced silicon diode thermometers (AdvSiDTs), which compared to SiDTs have the following advatages: (i) there are no electrical instabilities in the sensing elements, which makes the sensor completely stable at low temperatures; (ii) the ability to select the optimal operating current has been achieved, which allows expanding the scope of application of the thermometers, taking into account the requirements for minimizing power dissipation and signal-to-noise ratio; (iii) the possibility of using an operating current of 1 μA has been achieved, which makes it possible to minimize the measurement error caused by self-heating of the sensitive element, and to use the thermometers for precision measurements of low and ultra-low temperatures.

We present the results of experimental studies of current-voltage and temperature-voltage characteristics for AdvSiDTs in the temperature range 1.5-20 K and in magnetic fields up to 14 T. The measurements were carried out using the equipment of the International Laboratory of Low Temperatures and Strong Magnetic Fields in Wroclaw (Poland). A superconducting magnet produced by Oxford Instruments was used as a magnetic system, the field strength of which was controlled by the Oxford Object Bench program. The accuracy of maintaining the operating current of the thermometers was no worse than ±0.05%. The voltage measurement accuracy was no worse than ±0.05%. The temperature measurement error did not exceed ±0.03 K.

When studying the influence of the magnetic field on AdvSiDTs, the following features were experimentally discovered: (1) A weak negative magnetoresistance (MR) in magnetic fields up to 2 T, (2) With the increase of magnetic field from 2 T to 14 T, the MR becomes positive, and its behavior on the field varies from quadratic to square root dependence; (3) There is no influence of orientation of the thermometer in a magnetic field on the MR value.

The experimental results obtained are interpreted on the basis of ideas about the mechanisms of current transfer in heavily doped silicon diode structures (Mott hopping conduction through impurity centers, tunneling). Based on the analysis of the data obtained, the optimal operating regimes of AdvSiDTs at low temperatures and in magnetic fields of up to 14 Tesla were found.

Coexistence of Two Hole Phases in *p*-GaAs/AlGaAs Revealed by Surface Acoustic Waves Near Filling Factors 1 and 1/3

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We studied ac conductivity in a 17 nm wide *p*-GaAs/AlGaAs quantum well with hole concentration ~1.2×10^{11} cm^{-2} and mobility ~1.8×10^{6} cm^2/Vs (at 300 mK). The GaAs single quantum well was positioned between 100-nm undoped spacer layers of AlGaAs and was symmetrically δ-doped on both sides with carbon. We utilized the surface acoustic waves (SAWs) technique. A SAW propagated along the surface of a piezoelectric lithium niobate ($LiNbO_3$) delay line, and the two-dimensional hole system (2DHS) under investigation was pinned down on that surface of the $LiNbO_3$ crystal by means of springs. The AC electric field accompanying the SAW penetrated into the two-dimensional channel. The interaction of the SAW electric field with holes in the quantum well resulted in a change of the SAW attenuation and velocity. Our measurements of these SAW parameters performed in magnetic fields up to 18 T at SAW frequencies ranging from 30 MHz to 300 MHz, in the temperature interval from 20 mK to 300 mK, showed the presence of integer and fractional quantum Hall effects.

The ac conductivity of 2DHS $\sigma_{ac}=\sigma_1 - i\sigma_2$ was calculated from simultaneously measured SAW attenuation and velocity. Analysis of the conductivities σ_1 and σ_2 showed that at the filling factor $\nu = 1$ the carriers were localized in the minima of random potential with single-carrier hoppings between localized states, whereas at $\nu = 1/3$ the carrier state corresponded to the incompressible liquid. These are the commonly accepted phases for $\nu = 1$ and $\nu = 1/3$, respectively.

When ν deviated from 1 and/or 1/3, the temperature and frequency dependencies of σ_1, σ_2, and σ_1/σ_2 gradually changed and became drastically modified, thus signaling the transformation of the electrical conduction mechanism and a new 2D hole phase. To the best of our knowledge, a Wigner solid localization is the only one that can explain the observed frequency dependence of σ_2, in particular, negative values of σ_2 at low frequencies. Therefore, we associated the conductivity evolution with the formation of domains of the Wigner solid which were most pronounced at the lowest temperature at ν equal to 1.2 and 0.78, as well as 0.375 and 0.3. When the temperature rose, the domains melted as concluded by studying the frequency dependencies of σ_2. Although the Wigner solid has been previously observed in 2D *p*-GaAs/AlGaAs hole systems, we were able to detect it at the highest hole density and, consequently, the lowest hole-hole interaction ever reported. We explained the differences between the experimental data and the theoretical model [1] by the coexistence of Wigner crystal domains pinned by disorder and a hole Fermi liquid.

[1] M. M. Fogler and D. A. Huse, Phys. Rev. B **62**, 7553 (2000).

Room temperature antiferromagnetic resonance in NaMnAs

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Materials with an antiferromagnetic order have recently returned to the limelight of the condensed matter research [1-2]. NaMnAs is an antiferromagnetic I-II-V semiconductor with intriguing physical properties: (i) the Neél temperature is above the room temperature (~350 K) [3], (ii) NaMnAs exhibits a uniaxial magneto-crystalline anisotropy which appears to be significantly larger as compared to other common Mn-based antiferromagnetic compounds (e.g., 5 times larger than in MnF_2 or MnTe [4,5]). This anisotropy gives rise to the magnon gap energy comparable to rare-earth manganites [6].

Here we focus on magneto-optical properties of bulk single-crystal of NaMnAs. At low temperatures, we observe, in the collected magneto-transmission spectra, a single magnon mode at $\hbar\omega$ = 7 meV. Upon the application of the magnetic field along the tetragonal (c-) axis of NaMnAs, the magnon mode splits symmetrically into two branches that are linear in B. No interacting phonon modes in the vicinity are found. The observed response is thus a textbook example of classical antiferromagnetic resonance in easy-axis antiferromagnets. This finding is supported by magneto-transmission measurements in complementary configurations (B c). With increasing temperature, we observe a clear redshift of the magnon mode, reaching the energy of 5.4 meV at room temperature, see Fig. 1.

The experimental results are accompanied with linear spin-wave theory simulation of dispersion of magnon in k-space. The simulation is based on the experiment discussed above and on ab initio theoretical predictions of exchange interactions. Theoretical predictions are based on parameters coming from experimental observation. To calculate the spin-wave simulation, we apply software package SpinW written for MATLAB. By correlating simulation results with experiment, we are able to determinate single-ion anisotropy energy. The numerical results are confirmed by theoretical analysis of the magnon dispersion in momentum space.

We also briefly address other properties of NaMnAs, such as bandgap energy, directness of bandgap transition and energies of phonon modes.

Acknowledgements (Times New Roman 12 points, left-justified)

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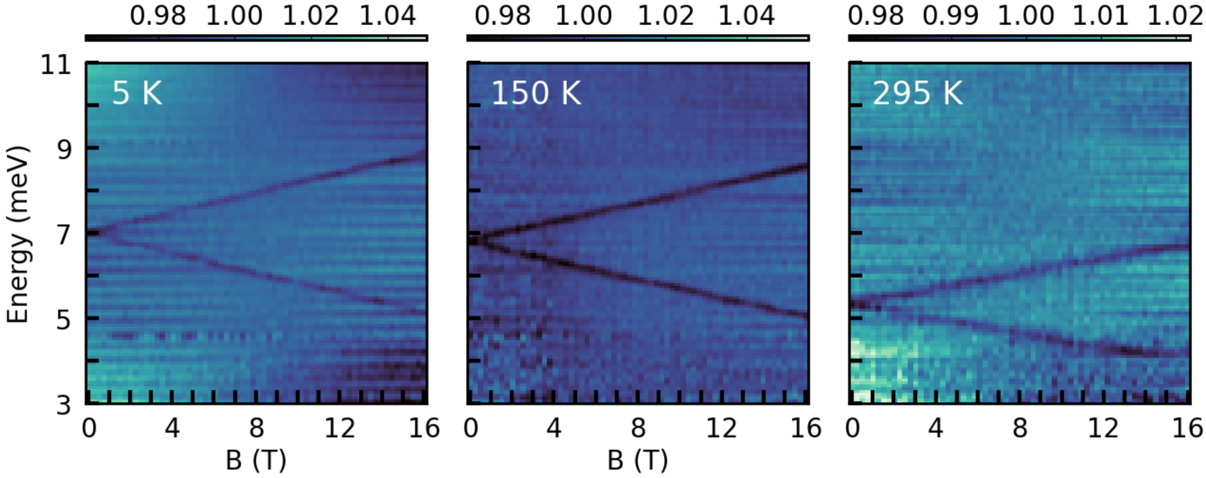

Fig. 1: Magnetic field dispersion of antiferromagnetic resonance observed in low energy IR transmission spectra - false color map $I(B)/I(B_{avg})$ at three given temperatures.

Quantum oscillations in the specific heat of graphite reveal hidden physics in Kittel

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We show that the electronic specific heat C_{el} in natural graphite exhibits a double-peak structure when a *single* spin Landau level crosses the Fermi energy. Crucially, such a double peak is not observed in other thermodynamic probes. At lower temperatures, the splitting decreases, and vanishes as $T \to 0$. Intriguingly, the double-peak structure is predicted by text book theory, $C_{el}/T = k_B^2 \int D(E)(-x^2 df/dx)dx$ where $f(x) = 1/(1+e^x)$, $x = E/k_BT$. The specific heat depends on the convolution of the Landau level density of states $D(E)$ and a kernel term $-x^2 df/dx$ which involves the first derivative of the Fermi-Dirac distribution function. The usual approximation (see e.g. Kittel), removing D(E) from the integral to obtain the well know formula $C_{el} = \frac{1}{3}\pi^2 D(E_F) k_B^2 T$, suppresses the double-peak structure which originates from the temperature dependent splitting of the double maxima in the kernel term. The calculated and predicted C_{el}/T are in excellent agreement, notably they reveal the highly asymmetric DOS of 3D Landau levels due to the van Hove singularity. The kernel term represents a spectroscopic tuning fork of width $4.8k_BT$ which can be tuned at will to resonance. Using a coincidence method, the double-peak structure can be used to accurately determine the g-factors of quantum materials. More generally, the tuning fork can be used to reveal any peak in the fermionic density of states which crosses the Fermi energy, such as for example Lifshitz transitions in heavy-fermion compounds.

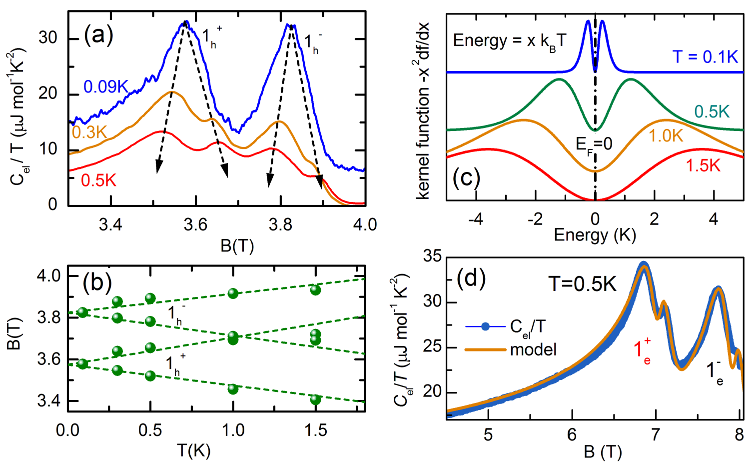

Figure 1: *(a) C_{el}/T versus B where the 1h spin Landau levels cross E_F in natural graphite. (b) Position of the double-peak structure versus temperature. (c) The kernel term plotted versus $E = xk_BT$. Maxima occur at x= ±2.4 (d) Measured and calculated C_{el}/T close to where the 1e spin Landau levels cross E_F.*

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Far-infrared spectroscopy of modulation-doped CdTe quantum wells at high magnetic fields

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Low-energy excitations of a two-dimensional electron gas (2DEG) in CdTe-based quantum wells (QWs) have been attracting researchers' attention for many years [1 - 3] . Typically, studies were devoted to single [1, 2] or double [3] QWs. In the present study we compare response of samples with one or ten QWs to far-infrared radiation.

Fourier spectroscopy measurements (transmission at 4.2 K) were carried out on samples with modulation-doped CdTe/$Cd_{0.7}Mg_{0.3}Te$ QWs. The wells were modulation-doped with iodine donors which resulted in appearance of a 2DEG in the wells. Samples differed by the width of the spacer or the width of the doping layers. In the case of multi-QW samples, neighbouring QWs were separated by a $Cd_{0.7}Mg_{0.3}Te$ barriers which were thick enough to consider the wells as no-interacting. Two types of samples were studied: as grown ones and samples with their surface covered with a Au grating of the period equal of 2 μm and 50% geometrical aspect ratio.

A high quality of samples studied (electron mobility of about 0.5×10^5 cm^2/Vs at 4.2 K at the concentration of about 10^{12} cm^{-2}) allowed us to observe a number of phenomena related to low-energy excitations of a 2DEG. Specifically, a cyclotron resonance (CR) was observed on all samples which led to determination of the cyclotron effective mass. The reststrahlen band in CdTe is situated at rather low energy and it coincides with the energy of the cyclotron resonance at magnetic fields about 15 T which leads to a polaron formation visible as deviation from linearity of the CR energy on B.

In samples with grid, we observed magnetoplasmon modes and their interaction with phonons. Also, interaction of the second harmonic of the CR with magnetoplasmons (i.e., Bernstein modes) were observed. This rich spectrum of magnetoplasma excitations is discussed within a model of the dielectric function which takes into account contributions from phonons and from nonlocal electron interactions.

This research was partially supported by the Foundation for Polish Science through the IRA Programme co-financed by EU within SG OP and within EFSE and the Polish National Science Centre grant UMO-2019/33/B/ST7/02858.

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Giant linear dichroism controlled by magnetic fields in the van der Waals magnet $FePS_3$

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Magnetic-field control of fundamental optical properties is a crucial challenge in the engineering of multifunctional microdevices. Van der Waals (vdW) magnets, which maintain magnetic orders even in atomically thin layers, offer a promising platform for hosting exotic magneto-optical functionalities owing to their strong spin-charge coupling. In this study, we demonstrate that a giant optical anisotropy can be controlled by magnetic fields in the vdW magnet $FePS_3$.

The giant linear dichroism (~11%), observed below T_N~120 K in the vdW magnet $FePS_3$, is switched to almost zero in a wide energy range from 1.6 to 2.0 eV by collapsing a robust zigzag magnetic order above 40 T. This remarkable phenomenon can be explained as a result of symmetry changes in the spin order allowing minority electrons in Fe^{2+} ions to hop ($d^6d^6 \rightarrow d^5d^7$ transitions) isotopically on a honeycomb lattice. Our research provides a striking idea for controllable anisotropic optical microdevices.

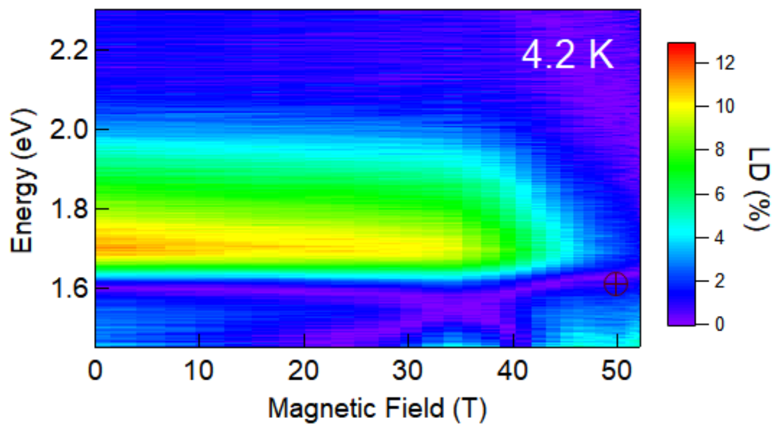

FIG. 1. Linear dichroism of $FePS_3$ in high magnetic fields.

Exploring thickness-dependent phonon structure in layered $Cr_2Ge_2Te_6$ ferromagnet

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Vast interest in layered materials with van der Waals (vdW) structures in the last decade resulted in renewed interest in two-dimensional magnets as well, which attributed to their promising applications. This intriguing category of materials holds great promise for advancements in spintronics nanotechnology and enhancing our understanding of magnetic phenomena within two-dimensional structures. Within the realm of magnetic vdW materials, $Cr_2Ge_2Te_6$ (CGT) stands out as a particularly captivating product. It falls into the uncommon category of ferromagnetic semiconductors, boasting a noteworthy Curie temperature (T_c) of approximately 61 K. Moreover, this material displays a ferromagnetic transition that depends on its thickness [1].

In this work, we examine Raman scattering (RS) measured in thin CGT flakes with different thicknesses, using a low excitation energy of 1.6~eV in a wide temperature range (T=5 – 300 K) and in high external magnetic field (0-8T). We also performed measurements on thin flakes subjected to the degradation process in ambient conditions.

The low-temperature (T=5 K) RS spectrum of the studied CGT flakes generally consists of 9 Raman peaks, as depicted in the Figure. These peaks can be categorized into two symmetry groups, E_g and A_g, a classification confirmed by polarization-resolved Raman experiments. Despite the typical redshifting behavior of Raman peaks with temperature, some exhibit high sensitivity to the transition through T_c. Specifically, the E_g^2, E_g^3, and E_g^4 peaks significantly depend on the transition from the ferro- to paramagnetic phase. Moreover, the A_g^4 mode is composed of a series of narrow lines, which diminish above the T_c. We also observed minimal degradation of the flakes in an air-exposed environment, in contrast to the findings reported for 2.3 eV excitation in Ref. [2].

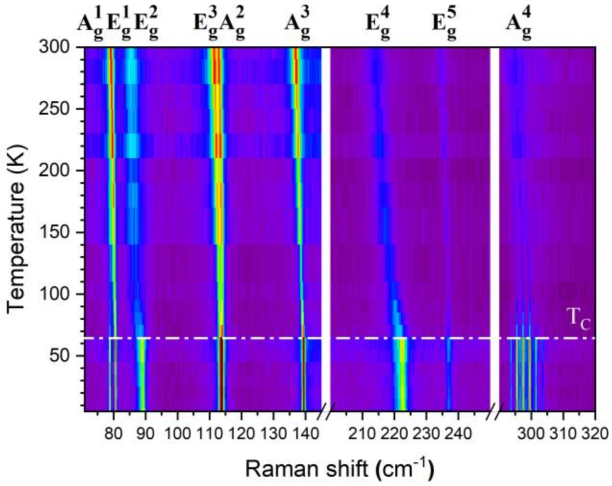

Figure: False-colour map of temperature evolution of the RS spectra measured on $Cr_2Ge_2Te_6$ flake. The T_c value is indicated by horizontal white dashed line.

Our results highlight that the electron-phonon interaction strongly depends on both thickness and degradation, suggesting potential significance for magneto-elastic coupling in magnetic layered materials.

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Nonlinear Hall effect in plan WTe2 with an in-plane magnetic field.

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Ongoing studies of nonlinear Hall effects and transport in 2D materials provide promising ways to probe the effects of Berry curvature. We consider gap narrowing in planar WTe2, which can be tuned by an out-of-plane electric field, inducing a transition from a topological insulator to a normal insulator. We use an effective tight-binding model to study this transition and confirm that the magnitude of the Berry curvature dipole (BCD) increases and reverses the sign across the band gap.

We further modify the band structure by applying a magnetic field in the plane. We find a strong dependence of BCD on both the magnitude and direction of the applied magnetic field near the band gap.

Rydberg series of intravalley excitons in WSe_2 multilayers

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Semiconducting transition metal dichalcogenides of group VI, exemplified by WSe_2, are well known for their prominent excitonic effects and transition from indirect to direct band gap when thinned down to the monolayer. While considerable efforts have elucidated the Rydberg series of excitons in monolayers, understanding their properties in multilayers is missing. In these structures, despite an indirect gap, momentum-direct excitons largely shape the optical response.

In this work, we combine the magneto-reflectance experiments with theoretical modeling based on the $\mathbf{k}\cdot\mathbf{p}$ approach to investigate the origin of the excitonic resonances in WSe_2 bi- tri- and quadlayers. For all investigated thicknesses, we observed a series of excitonic resonances in the reflectance spectra, initiated by a ground state with an amplitude comparable to the ground state of the 1s exciton in the monolayer. Higher energy states exhibit a decrease in intensity with increasing energy, which could suggest that these are the subsequent ns states of the Rydberg series. However, the lack of a significant increase in diamagnetic shift for these lines in magneto-reflectance experiments indicates the presence of several non-degenerate exciton series for tri- and quadlayers. Moreover, the analysis of the diamagnetic shifts allowed us to identify the Rydberg series index n of the observed transitions.

Theoretical analysis of $\mathbf{k}\cdot\mathbf{p}$ model for N-layer ($N = 2, 3, 4$) reveals the fine structure of the bands in its $K^{\pm}$ valleys. The conduction bands become N times degenerated, while a crystal field of the multilayer hybridizes the valence band states of adjusted layers. As a result, N different types of optical transitions are allowed at the $K^{\pm}$ point of N-layer, which leads to the formation of N different types of excitons. Further analysis of such excitonic states revealed that the bilayer hosts two degenerate momentum-direct exciton series, consistent with our experimental findings of a single Rydberg series to the 4s state. Theoretically predicted three and four different excitonic series in tri- and quadlayers, explain our experimental observation of two 1s and one 2s states in trilayers and four 1s and two 2s states in quadlayers.

Geometric engineering of viscous magnetotransport in a two-dimensional electron system

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In this study, we present our experimental investigation on the magnetotransport properties of a two-dimensional electron system in GaAs quantum wells utilizing a variety of device geometries, including obstacles with thin barriers and periodic width variations. Our primary focus is to explore the impact of these geometries on the electron viscous flow parameters, enabling precise manipulation of hydrodynamic effects under controlled conditions. Through an analysis of the large negative magnetoresistivity and zero field resistivity, we deduce the scattering times for electron-electron and electron-phonon interactions, as well as the effective channel width.

Viscous electron flows are expected to manifest in resistivity when the mean free path for electron-electron collisions is considerably shorter than the mean free path resulting from impurity and phonon scattering. Geometry plays an essential role in hydrodynamic flow. Studying the magnetohydrodynamic behavior of electron transport significantly enhances our comprehension of viscous transport, enabling us to extract key parameters like electron-electron scattering rates and slip length.

In the current study, we have conducted experimental investigations on the transport properties of a mesoscopic 2D electron system in GaAs quantum wells with various geometries (figure 1a,b,c) For all configurations we observe a giant negative magnetoresistance at low magnetic field [1]. By analysing this pronounced negative magnetoresistivity and the resistivity in zero magnetic field, we extract the scattering times associated with electron-electron and electron-phonon interactions [1]. Furthermore, we determine the effective width of the channel utilized in these experiments, which is found to be coincident with the geometric width within an order of magnitude variation. Our findings confirm that the system under investigation serves as a tunable experimental platform for investigating hydrodynamic transport regimes at temperatures above 10 K (figure 1d).

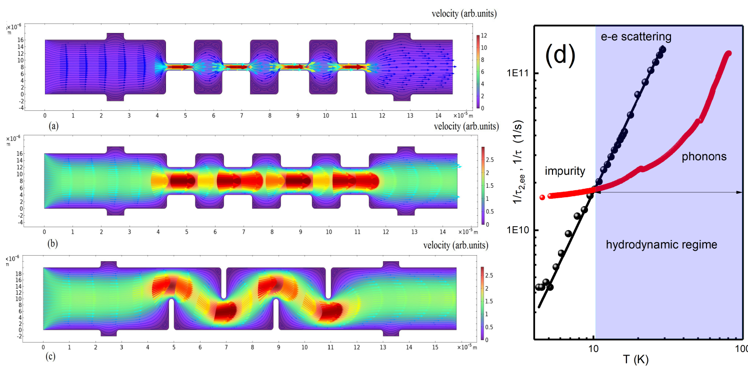

Figure 1: (a,b,c) Sketch of the velocity flow profile in a device with different configurations. (d) The relaxation rates as function of temperature. The blue shading highlights the temperature range indicating the presence of the hydrodynamic regime.

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Pseudospin Quantum Hall Ferromagnetism Probed by ESR

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At low temperatures, the multi-component two-dimensional electron systems (2DES) possess a rich physics with a set of unconventional ground states and a non-trivial spectrum of various charge and spin excitations. The generally accepted approach to describe the complex behavior of such structures implies the introduction of an additional internal degree of freedom of an electron, which is in many respects similar to spin and is therefore often called pseudospin by analogy. The close analogy between spin and pseudospin degrees of freedom suggests the existence of such phenomena as pseudospin ferromagnetism stabilized by electron-electron interactions and the corresponding quantum phase transitionsr [1,2]. The investigation of pseudospin ferromagnetism remains of increasing interest since many of the novel atomically thin semiconductors possess such a degree of freedom either in the form of a valley or a layer [3,4].

In present work we study the effect of the pseudospin ferromagnetism with the aid of an electrically detected electron spin resonance in a wide AlAs quantum well containing a high quality two-dimensional electron system. Here, pseudospin emerges as a two-component degree of freedom, that labels degenerate energy minima in momentum space populated by electrons. The built-in mechanical strain in the sample studied imposes a finite “Zeeman” splitting between the pseudospin “up” and “down” states. Due to the anisotropy of the electron spin splitting we were able to independently measure the electron spin resonances originating from the two in-plane valleys. By analyzing the relative resonance amplitudes, we were able to investigate the ferromagnetic phase transitions taking place at integer filling factors of the quantum Hall effect when the magnetic field is tilted. The pseudospin nature of these transitions is demonstrated.

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Universal Long-Range Magnetic Proximity Effect in Ferromagnet – Semiconductor Quantum Well Hybrid Structures

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Integrating magnetism into solid-state electronics is important for developing devices where information processing and its storage are located within a single chip. Hybrid ferromagnet (FM) – semiconductor (SC) structures are promising in this field because of strong and tunable coupling between spin systems of FM and SC. In particular, in structures consisting of a FM layer and a SC quantum well (QW) separated by a non-magnetic barrier, a long-range ferromagnetic proximity effect is observed [1-5]. This effect consists in the effective p-d exchange interaction between d-electrons of the FM and heavy holes bound to acceptors (p-system) in the QW on distances exceeding the carrier wave function overlap. The interaction is established via the phononic Stark effect [1]: holes in the QW are polarized by chiral acoustic phonons carrying angular momentum from the magnetized FM. This also can be understood as effective magnetic field (reaching about 2.5 T) acting on holes from the FM.

In our recent study the long-range magnetic proximity effect is observed in hybrid structures consisting of 10 nm CdTe QW and semimetal (magnetite Fe_3O_4) or dielectric (spinel $NiFe_2O_4$) FM layer separated by a nonmagnetic $Cd_{0.6}Mg_{0.4}Te$ barrier [5]. Together with our previous findings [1-4] this shows that the exchange interaction mediated by chiral phonons has a universal nature and is observed in FM-QW structures 1) with diverse FM constituents: metals (Fe, Co), semimetals (magnetite), dielectrics (Ni spinel), and 2) with potential barriers for charge carriers of different thicknesses (1 − 40 nm) and different height ($Cd_{0.6}Mg_{0.4}Te$ and $Cd_{0.8}Mg_{0.2}Te$). Such universality of the phononic mechanism is explained by the following 1) the energy of the chiral acoustic phonons is close to 1 meV for many common ferro- and ferrimagnetic materials and 2) the structures have various potential barrier for charge carriers but not for acoustic waves, so phonons propagate into the SC over distances significantly exceeding the wave function overlap of charge carriers with the FM. Moreover, the mechanism of long-range exchange interaction through chiral phonons does not impose high requirements on the quality of the interfaces.

The ubiquitous presence of the long-range exchange interaction along with the possibility of its electrical control [3] offers prospects in the development of low-voltage spintronic devices compatible with existing semiconductor electronics.

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The temperature influence on the brightening of neutral and charged dark excitons in WSe_2 monolayer

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The monolayer (ML) of WSe_2 belongs to the widely investigated family of semiconducting transition metal dichalcogenides (S-TMDs). Due to the arrangement of the spin-split and spin-polarized subbands at K points, the low-temperature (T=5 K) photoluminescence (PL) spectra of high-quality WSe_2 ML encapsulated in hBN flakes display a series of emission lines. They were ascribed to the variety of excitonic complexes, *e.g.* neutral bright (X^B) and dark ($X^{G/D}$) excitons, biexcitons, and their phonon replicas, but the majority of them are associated with the spin-forbidden dark states [1]. The most known approach to brighten the dark states is the application of the in-plane magnetic field, which results in the extraordinary enhancement of the $X^{G/D}$ line at 5 K [2].

In this work, we examine the influence of temperature on the brightening of dark complexes, *i.e.* so-called neutral grey (X^G) and dark (X^D) excitons, and negative dark trion (T^D), in WSe_2 ML encapsulated in hBN by performing the PL experiment. The measurements were performed in a temperature range from 4.2 K up to 100 K and in an external magnetic fields applied parallel to the ML plane ($B_\parallel$) up to 30 T.

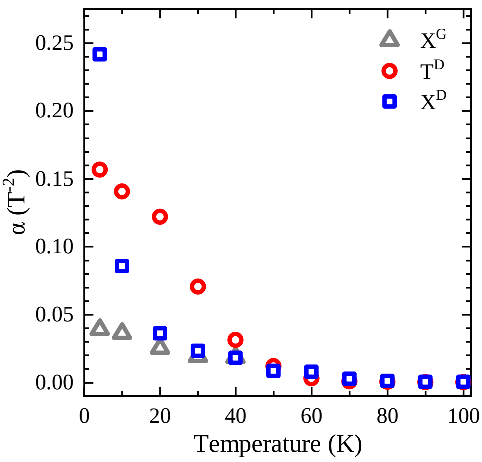

Figure 1: The extracted α parameters as a function of temperature.

We found that while at 4.2 K, the brightening effect of dark excitons is so substantial that a few tesla is enough that the $X^{G/D}$ lines are a few times larger than the X^B line. However, increasing the temperature leads to a rapid vanish of this effect, and hence the dark exciton emission is barely visible at 100 K only at the highest $B_\parallel$ values.

The analysis of the integrated intensities (I) of the X^G, X^D, and T^D lines as a function of $B_\parallel$ reveals their quadratic dependences, which can be described by formula $I \approx \alpha B_\parallel^2$. The α parameter refers to as the brightening coefficient, which is proportional to the population of the dark excitons and the emission intensity of the bright excitons [3].

Figure 1 represents the temperature evolutions of the extracted α parameters for the X^G, X^D, and T^D complexes. At 4.2 K, the α parameter is the biggest for the X^D lines and with a value of about 0.24 T^{-2} is much bigger as compared with the X^G (0.15 T^{-2}) and T^D (0.04 T^{-2}) ones. The α of X^D decreases drastically, more than five times, with an increase in temperature from 4.2 K to 20 K, which is followed by a slower reduction at higher temperatures. As the α decrease for X^G is much slower, the α values for the X^G and X^D complexes reach almost the same value at 40 K. Interestingly, the α parameter of the T^D line is the biggest from 10 K to 40 K. In the range of 50 K - 100 K, the α values for the X^D and T^D are almost at the same level and the X^G line is no more apparent in the spectra.

Our results indicate that the population of dark excitons and trions plays a very important role in emission processes in the temperature range below about 100 K, while due to the increase kinetic energy of carriers at higher temperatures it became impossible to observe emissions related to dark states.

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Magnetic field enhancing of THz photocurrent in AlGaN/GaN-based asymmetric grating-gate plasmonic crystals

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The grating-gate plasmonic crystals, that incorporate a 2D electron gas (2DEG) within the AlGaN/GaN interface and integrate a grating-gate electrode, hold great potential for designing highly efficient and cost-effective devices in the Terahertz (THz) range [1].

In this work, we report THz-induced ratchet photocurrent in AlGaN/GaN plasmonic crystal superimposed with asymmetric dual grating-gate coupler (see insets in Fig.1). Asymmetry is added for the effective THz radiation detection using periodic structures, as well as it defines the direction of the THz ratchet photocurrent [2].

The increase of magnetic field results in the signal alternating oscillations with the amplitude by orders of amplitude larger than the signal obtained at zero magnetic field (fig.1). Comparison of the observed oscillations with the SdH magnetoresistance oscillations demonstrates that at high magnetic fields both photocurrent and resistivity oscillations have the same period and phase. Moreover, the envelope of the oscillations exhibits large beatings as a function of the magnetic field. We demonstrate that this effect is caused by spin-orbit (SO) interaction which dramatically modifies the ratchet effect in the magnetic field in the regime of Shubnikov-de Haas (SdH) oscillations.

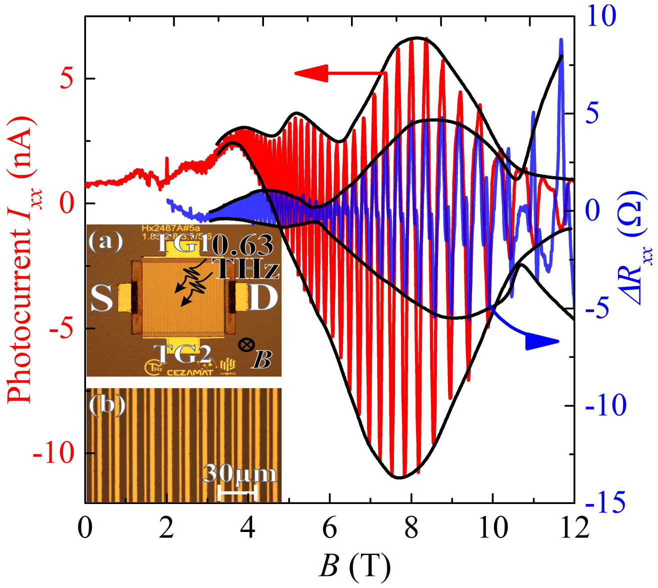

Fig. 1. Photocurrent and magnetoresistance in SdH oscillations regime as a function of the magnetic field measured at 4.2K. Oscillation envelopes are shown by black solid lines as the guides for the eye. Insets illustrate Nomarski contrast microscope photos of the investigated plasmonic crystal (a), where TG1 and TG2 – two multi-finger top gate electrodes, S and D – source and drain electrodes respectively, (b) Magnified active region of the asymmetric grating-gate plasmonic crystal.

Our results provide a novel method to improve THz detection and to study the SO band splitting. THz photoconductivity in magnetic fields allows extracting SO splitting constant, which is in good agreement with values obtained by widely used techniques: direct measurements of magnetoresistance in SdH oscillations regime, the weak anti-localization experiments, optical methods, and photogalvanic studies. Since SdH oscillations in the magnetoresistance regime and ratchet photocurrent correlate, these two experimental methods are complementary, which gives the opportunity to verify the results.

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Strong coupling of magnetoplasmons to Faby-Pérot cavity modes

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Strong light-matter coupling forms polariton states, which are hybridized modes of electromagnetic cavity fields and a dipolar-active matter transition. In the terahertz (THz) range of frequencies strong coupling can be achieved with many solid-state quasi-particles, such as phonons, magnons [1], or plasmons in two-dimensional electron gases (2DEG) [2]. Here, we consider cyclotron resonance and magnetoplasmons excited in a high electron mobility 2DEG based on GaAs/AlGaAs heterostructures coupled with Fabry-Pérot cavity modes formed by the sample substrate itself. We show that a strong coupling of excitations of two-dimensional electron gas can be observed achieved with Fabry-Perot cavities of hundreds of µm dimensions. We show that the coupling strength is tuned with electron concentration.

During the experiments, samples were cooled down to 10 K in an optical cryostat with quartz windows. We used a THz time-domain spectrometer to measure reflection from our samples fixed on a copper holder. Pulses of THz radiation were guided from an emitter to the sample using two parabolic mirrors, and the reflected beam was collected to the detector using an identical set of parabolic mirrors. The incident beam was 10 degrees. We measured time-domain reflection traces as a function of the magnetic field, up to 2.5 T. We performed a fast Fourier transform and we obtained reflection spectra.

We prepared a sample patterned with rectangular 2DEG mesas of 3.1 µm side length ordered in a rectangular lattice with a period of 7.6 µm. In a reference sample without patterning, we observed polariton modes formed, manifested as avoided crossings of the cyclotron resonance with a series of cavity modes. Cavity modes in these series are spectrally separated by about 0.12 THz, which is mostly related to the thickness of the substrate and its dielectric constant. In a sample with patterning, we observed, as a function of the magnetic field, magnetoplasmons, and edge magnetoplasmons, both of which interact with the cavity modes. We observed that the coupling of plasmons with cavities is quenched when the second harmonic of the cyclotron resonance has a similar frequency. This observation poses basic questions on the mechanism of light-plasmon coupling in two-dimensional electron gases under strong magnetic fields, when Bernstein modes are excited [3].

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Quantum Anomalous Hall Effect as a Universal Rotation Gauge

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Integer quantum Hall effect allows to gauge the resistance standard up to more than one part in a billion. Combining it with the speed of light, one obtains the fine-structure constant $\alpha \approx 1/137$, a dimensionless reference number that can be extracted from a physical experiment. Most exact notion of this value and especially its possible variation on the cosmological time scales is of enormous relevance for fundamental science. In an optical experiment, the fine-structure constant can be directly obtained as purely geometrical angle by measuring the quantized rotation of light polarization in two-dimensional quantum wells. In realistic conditions, high external magnetic fields have to be applied, which strongly affects possible attainable accuracy. An elegant solution of this problem is provided by quantum anomalous Hall effect where a universal quantized value can be obtained in zero magnetic field.

We report the measurement of the fine-structure constant in a direct optical experiment that requires no material adjustments or technical calibrations [1]. By investigating the Faraday rotation at the interference maxima of the dielectric substrate, the angle close to one α is obtained at liquid helium temperatures without using a dilution refrigerator, see the Figure. Such calibration and parameter-free experiment provides a system-of-unit-independent access to universal quantum of rotation.

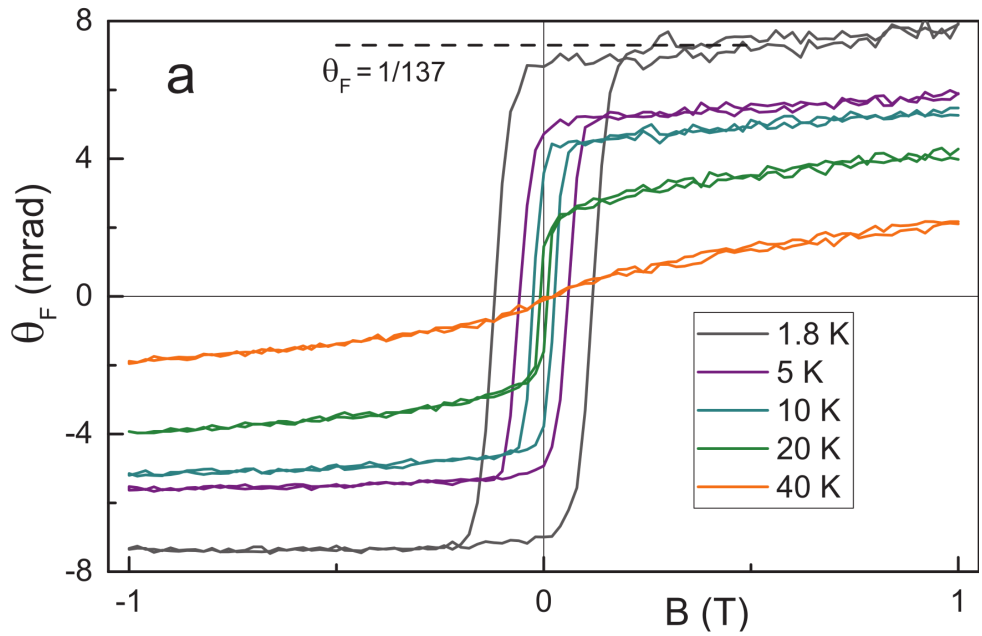

Figure 1: Step in the magnetic field dependence of the Faraday rotation equal to the fine-structure constant.

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Quarter- and Half-Filled Quantum Hall States and their Competing Interactions in Bilayer Graphene

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Bilayer graphene has emerged as a key platform for studying non-Abelian fractional quantum Hall (FQH) states [1, 2, 3]. Its multiple half-filled plateaus with large energy gaps combined with its tunability offer an opportunity to distill the principles that determine their topological order. Here, I will present the observation of four additional plateaus at $\nu = \frac{1}{2}$ for different spin and valley, revealing a systematic pattern of non-Abelian states according to their Levin–Halperin daughter states. In the $N = 0$ levels, where half-filled plateaus are absent, we instead observe four unexpected incompressible quarter-filled states along with daughters. The mutual exclusion of half- and quarter-filled states indicates a robust competition between the interactions favoring either paired states of two-flux or four-flux composite fermions [4].

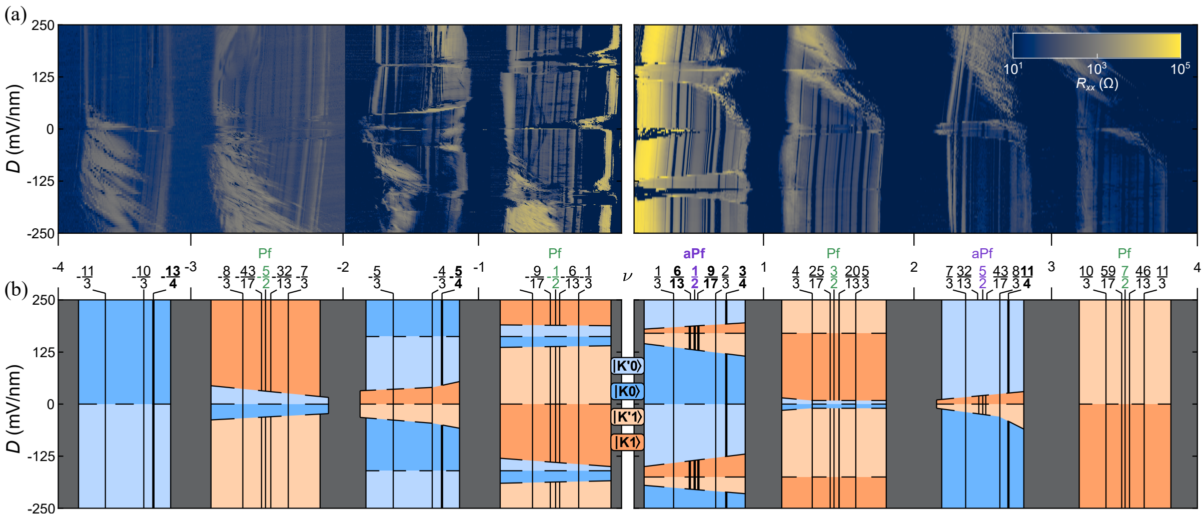

Figure 1: (a) R_{xx} as a function of ν and D. Dark-blue areas mark incompressible states where $R_{xx} < 10\ \Omega$. (b) Schematic of all even- and selected odd-denominator FQH states observed in (a). Bold vertical lines mark newly observed states. Dashed lines mark valley and orbital crossings in the ν–D phase space. Green and purple labels indicate Pfaffian (Pf) and anti-Pfaffian (aPf) states, respectively, according to their Levin–Halperin daughter states. Figure adapted from Ref. [4].

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Spectroscopy Studies of WSe2 doped with Cobalt and Vanadium

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Diluted magnetic semiconductors (DMS) hold significant potential for their unique physical properties and spintronic applications. Introducing magnetic ions into transition metal dichalcogenides (TMDs), such as WSe_2, can provide new functionalities in these two-dimensional (2D) semiconductors. Previous studies have indicated that WSe_2 displays weak ferromagnetism, which can be augmented by doping with cobalt ions. Additionally, doping TMDs facilitates the fabrication of thin-film transistors. However, vanadium doping has been reported to quench photoluminescence (PL) and increase defect densities, potentially due to the increased density of positive trions.

In this study, we explore how PL varies with different concentrations of cobalt and vanadium in WSe_2. We support PL by Electron Spin Resonance (ESR) measurements of the bulk WSe_2 doped with cobalt. Few-layer structures were prepared from bulk WSe_2 crystals doped with cobalt and vanadium up to 2%, using a golden tape exfoliation technique on SiO_2 substrates. This method yielded large-area monolayers, with some bi- and tri-layers also identified. The PL intensity was significantly lower in bi- and tri-layers compared to monolayers. Monolayer spectra exhibited a broad exciton line around 1.72 eV, followed by an intense PL band likely due to donor-acceptor recombination centered at 1.62 eV. Notably, doped WSe_2 samples showed PL intensities an order of magnitude higher than undoped ones. Moreover, the ratio of donor-acceptor to exciton transition intensities was higher in doped samples than in pure WSe_2. Statistical analysis revealed no direct correlation between the doping level and PL intensity. This suggests that cobalt and vanadium doping enhance PL in few-layer WSe_2, possibly due to p-type counter-doping effects when Co and V act as acceptor dopants. Further investigations are ongoing, focusing on WSe_2 monolayers encapsulated in hexagonal boron nitride (hBN) to confirm these findings. Moreover, ESR studies showed the presence of an intense signal in WSe_2 doped with cobalt, which does not occur in undoped samples. The signal is characterized by significant angular dependence and vanishes in temperatures above 40 K. This observation also suggests that doping of WSe_2 affects its electric properties, which are under further study.

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Anomalous Sub-THz Photoresponse in Graphene-based Field Effect Transistor

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Plasmonic technology that uses field effect transistors (FETs) is a promising platform for terahertz (THz) detection applications owing to their high operational speed and on-chip fabrication technology. Here, we investigated the sub-THz-induced photocurrent response in a graphene-based back-gated FET over a wide range of temperatures and magnetic fields. The mobility, determined through magnetoresistance measurements was between 76,000-72,000 cm²/Vs within the 10-100 K temperature range. At low temperatures, the experimentally observed gate voltage dependence of the sub-THz-induced photocurrent displayed distinct peaks, deviating from the well-known non-resonant photoresponse. Experiments in magnetic fields and sources with different THz frequencies confirmed that the observed sub-THz-induced photocurrent does not comply with the resonant and non-resonant plasmon detection mechanisms. Additional investigations, particularly under high magnetic fields and with high-frequency sources (such as QCL) will help to understand the underlying mechanism of such detection.

Keywords: graphene; photocurrent; non-resonant detection; plasmons