Załącznik nr 3 (autoreferat w języku angielskim).

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2. Degrees and Diplomas
    - September 1999. Master degree in Physics. Thesis: *Tunelowanie w strukturach z pojedynczą barierą AlAs* supervised by dr Jacek Przybytek
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4. Scientific Accomplishment:
    a) Title: Electron transport in GaAs-based structures for spintronics

    b) List of publications

B1. R. Giraud, **M. Gryglas**, L. Thevenard, A. Lemaître, and G. Faini, *Voltage-controlled tunneling anisotropic magnetoresistance of a ferromagnetic $p^{++}$-(Ga,Mn)As/$n^{+}$-GaAs Zener-Esaki diode,* Appl. Phys. Let. **87**, 242505 (2005).

B2. B. Jouault, **M. Gryglas**, M. Baj, A. Cavanna, U. Gennser, G. Faini, D. K. Maude, *Spin filtering through a single impurity in a GaAs/AlAs/GaAs resonant tunneling device,* Phys. Rev. B, **79**, 041307(R), (2009).

B3. **M. Gryglas-Borysiewicz**, A. Kwiatkowski, M. Baj, D. Wasik, J. Przybytek, and J. Sadowski, *Hydrostatic pressure study of the paramagnetic-ferromagnetic phase transition in (Ga,Mn)As*, Phys. Rev. B **82**, 153204 (2010).

B4. P. Juszyński, **M. Gryglas-Borysiewicz**, J. Szczytko, M. Tokarczyk, G. Kowalski, J. Sadowski, D. Wasik, *Magnetic anisotropy investigations of (Ga,Mn)As with a large epitaxial strain*, Journal of Magnetism and Magnetic Materials **396**, 48 (2015).

B5. **M. Gryglas-Borysiewicz**, A. Kwiatkowski, A. Lemaître, J. Przybytek, K. Budzik, Ł. Balcerzak, M. Sawicki, D. Wasik, *Magnetotransport Investigations of (Ga,Mn)As/GaAs Esaki Diodes under Hydrostatic Pressure*, Applied Surface Science, **396**, 1875 (2017).

B6. **M. Gryglas-Borysiewicz**, P. Juszyński, A. Kwiatkowski, J. Przybytek, J. Sadowski, M. Sawicki, M. Tokarczyk, G. Kowalski, T. Dietl and D. Wasik, Hydrostatic-pressure-induced changes of magnetic anisotropy in (Ga,Mn)As thin films, accepted in the J. Phys.: Condens. Matter and available at: https://doi.org/10.1088/1361-648X/aa546d

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c) Description of the scientific goals of the above mentioned work, obtained results and prospect of applications

## 4.1. Introduction

The name „spintronics" by analogy to electronics was given in the late 90' to the concept of electronics based on the spin degree of freedom [1,2]. In order to take advantage of spin of electron, one should master: creating spin polarized carriers, spin injection process into the device region, where operations on spins are performed, and finally ensure spin read-out. In all these processes the very fundamental problems of spin coherence within material and spin relaxation during the charge transfer must be addressed.

An important contribution to the field of spintronics was made in Poland, where starting from the 70', semiconductors with the transition metal ions, mainly II-VI, were intensively studied, so called diluted magnetic semiconductors [3-9]. One of the main achievements was the discovery and description of the exchange interaction between the electron spins localized on magnetic ions and spins of delocalized electrons. The exchange splitting within the valence or conduction band was a method to obtain net spin polarization of carriers when magnetic field was present. In the meantime, the intensive investigations of IV-VI semiconductor compounds, *yielded the discovery of* the ferromagnetic phase, for which the presence of free carriers was essential [10-12]. For II-VI semiconductors, the transition metal ions are isoelectronic impurities and unless codoped the materials are insulating. For III-V compounds, those ions provide both the magnetic moment and free carriers. However, due to very low solubility of the magnetic elements, it was not possible to introduce them in sufficiently high amounts[1]. A breakthrough came with the introduction of low temperature molecular beam epitaxy (LT-MBE) for the growth of $In_{1-x}Mn_xAs$ with high Mn content (x reaching 0.18), with homogenious Mn distribution and paramagnetic character [13]. Soon after that, ferromagnetic phase was obtained, first for $In_{1-x}Mn_xAs$, with a Tc of the order of 7K [14] and for (Ga,Mn)As, with relatively large Tc reaching 110 K [15,16][2]. These discoveries have triggered a huge scientific interest in the ferromagnetic semiconductors, and in (Ga,Mn)As in particular.

Since (Ga,Mn)As is highly relevant to this work, a brief description of its properties is due. A huge scientific effort made to the date [17], both experimental and theoretical one, enabled a good understanding of most physical properties of GaMnAs. It is known that $Mn_{Ga}$ at low concentrations is a shallow acceptor ($A^{-/0}$ with the binding energy of about 100 meV) in $Mn^{2+}$ ($3d^5$) electronic configuration. It introduces localized magnetic moment S=5/2. Manganese may however take interstitial position, in which it is a double donor, aniferromagnetically couples to the substitutional Mn [20]. This leads to a partial compensation of free carriers and magnetization. Due to the low temperature of growth there are some other defects, typical of LT-GaAs [21], e.g. As antisite ($As_{Ga}$), which is a double donor.

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[1] e.g. the record Mn content in bulk (Ga,Mn)As crystals was about 0.05%

[2] The current record value of Tc in (Ga,Mn)As reaches 200K. There are no clear ways to follow to increase that number. Nevertheless, the investirations are still ongoing, as they help to understand the problems of metallic spintronics (e.g. [18],[19]).

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The low temperature of growth influences the electrical parameters of GaMnAs, both carrier concentration and mobility. Not only the absolute values of the resistance $\rho$ are important, but also its temperature dependence. Typically, there are two tendencies observed: one with the resistance roughly constant as a function of temperature, referred to as 'metallic', with a maximum close to Tc. Second, showing insulating character, with the rise of resistance as temperature is decreases. There is an interesting problem of the relation between the value of Tc and carrier concentration. For very small Mn contents the samples are paramagnetic and show insulating character with typical hopping conductivity. There is however such Mn content range where the sample is still in the insulating regime, but already showing ferromagnetic behavior. For even higher Mn contents and hole concentration, the Tc is further increased. The fundamental role of free carriers for ferromagnetism in GaMnAs was theoretically described within p-d Zener model [22, 23]. For large concentrations of holes, long range magnetic ordering comes from exchange interaction between localized spins on $3d^5$ shell of Mn with delocalized holes. In the intermediate case, the two fluid description enters, in which a part of holes is localized at pairs of $Mn^{+2}$ ions, forming magnetic polarons, which interact via free holes- the second part of hole fluid. For the extreme case of no free carriers, the ferromagnetic phase does not occur.

The Hamiltonian describing interaction between delocalized and localized holes for Mn content equal to x, is given by: $H= -N_0 J_{pd}\, x\langle S\rangle\cdot s$, where $N_0$ is concentration of cation sites, $x\langle S\rangle$ their effective spin (i.e. $\mu_B g\cdot N_0 x\langle S\rangle$ is the magnetization of localized spin system), s is the spin of electron (hole) and $J_{pd}$ is the exchange coupling constant. This interaction leads to pronounced changes of the valence band structure of (Ga,Mn)As in respect to GaAs: the light and heavy hole subbands are no longer degenerate at $\Gamma$ point, different densities of states are observed for spin up and spin down and the Fermi surface is highly anisotropic and depends on magnetization orientation. Another reason for its anisotropy is the structural anisotropy. (Ga,Mn)As layers are MBE-grown on buffer layers, which impose the in-plane lattice constant to (Ga,Mn)As. For GaAs buffer the layer is compressively strained, for InGaAs buffers (usually) there is a tensile strain. The strain in the plane of the layer imposes strain in the growth direction, and both further modify anisotropy of the valence subbands. The valence band anisotropy in turn, entails the magnetic anisotropy of the (Ga,Mn)As[3]. The numerous origins of anisotropy give many possibilities to influence it, by e.g. temperature changes [24, 25], concentration modifications [26] or strain [27, 28]. The latter problem of strain impact on magnetic anisotropy of GaMnAs was developed in this work, both for epitaxial strain [B6] and hydrostatic pressure [B4] which also affects the Curie temperature as shown in [B3]

The first spintronic application of (Ga,Mn)As came early after its discovery [29]. (Ga,Mn)As was used as a source of spin polarized carriers in an Esaki diode, in which p-type (Ga,Mn)As was grown on n-type GaAs. The spin polarization was detected optically by measurements of polarization of light in a quantum well neighbouring the junction [29, 30]. Due to the presence of the tunnel barrier, the spin injection process was very efficient [31] and spin polarization of the injected carriers exceeded 80% [32]. The (Ga,Mn)As /GaAs Esaki diode is an interesting system for the studies of (Ga,Mn)As properties. In contrast to most standard transport techniques, where electrons at Fermi level take part in the current, a possibility of applying bias gives access the densities of states far below the Fermi level. This aspect was highly exploited in the investigations performed [B1, B2, B5].

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[3] For thin magnetic layers the contribution of demagnetization field may be equally important. Moreover, there is also uniaxial in-plane anisotropy, attributed to Mn-Mn dimmers, preferentially aligned along [-110].

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## 4.2. Description of the scientific accomplishment

Two fundamental problems of spintronics, material properties and spin transfer, are investigated in this work. The studies were realized on (Ga,Mn)As layers grown on different buffers on a single barrier tunnel structure GaAs/AlAs/GaAs and on Esaki diodes (Ga,Mn)As/GaAs. Experiments were performed with electron transport methods, in the temperature range 1.5 K – 200 K and in magnetic field up to 12T. When needed, complementary magnetization measurements (SQUID) and X ray diffraction were used. To our knowledge, the influence of hydrostatic pressure on (Ga,Mn)As/GaAs diodes was investigated for the first time.

One of the main outcomes of the presented investigations is the determination of hydrostatic pressure influence on the Curie temperature, revealing the different role of pressure for metallic and insulating samples. Magnetic anisotropy of (Ga,Mn)As was thoroughly studied for epitaxially strained (Ga,Mn)As layers and for layers subjected to hydrostatic pressure. Anisotropy of valence band subbands was investigated with GaMnAs embedded into an Esaki diode. Different contribution of subsequent subbands was clearly resolved and it remained unaltered by hydrostatic pressure. The I(V) characteristics of the diodes were analyzed, pointing to the important contribution of states present in the forbidden gap, possibly in (Ga,Mn)As. For Esaki diodes the spin polarization of carriers was introduced by exchange splitting of the bands. In GaAs/AlAs/GaAs structures spin polarization was achieved by the application of magnetic field (via Zeeman effect). The features observed in the tunnel current showed that spin was conserved in the tunneling process.

## 4.3. Description of the works constituting the scientific accomplishment

The first work [B1] was motivated by the discovery made by Ch. Gould et al. from the group of prof. Molenkamp in Wuerzburg [33]. They have studied a single (Ga,Mn)As layer separated from the metallic contact by a thin insulator layer, acting as a tunnel barrier. They have observed two-state resistance switching while magnetic field was varied in the plane of the layer. Such spin valve behavior was known to occur in metallic magnetic layers. The effect, called tunneling anisotropic magnetoresistance (TAMR) is a consequence of the valence band (and subbands) anisotropy of (Ga,Mn)As. The density of states within each subband changes when magnetic field is altered, which affects the tunnel current. Such changes may be observed if the in-plane momentum is at least partially conserved. Thus, an effort was made to study these effects in GaAs/(Ga,Mn)As Esaki diode, where a natural barrier resulting from the band alignment and depletion layer is formed. This system was also promising after late reports on very high spin injection efficiency [32].

GaMnAs/GaAs Esaki structures were obtained by MBE. The diodes were processed by means of optical lithography and mesa etching and appropriate metallizations were made in order to ensure Ohmic contacts to the top and bottom the mesa. The studied samples had Tc of the order of 50 K and easy axis of magnetization in the plane of the layer. Measurements of current-voltage characteristics were performed at low temperature with magnetic field perpendicular to the layer and with no magnetic field. TAMR [4] effect was observed: the value of resistance showed a strong dependence on the magnetization vector (tuned by magnetic field) and interestingly, for some values

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[4] Strictly speaking resistance is not a correct notion for samples showing nonlinear I(U) characteristics. Still, it is commonly used, by analogy to metallic systems and usually R= U/I.

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of polarization the current was increased and for some other decreased. The non-monotonic behaviour of TAMR was qualitatively understood, as being due to contribution of individual valence band subbands. Thus, this effect gives insight on the detailed electronic structure of the valence band. The experimental results were later confirmed by theory [34], in which Authors have obtained the non-monotonic bias dependence of TAMR.

The tunneling of spin polarized carriers is investigated in [B2]. We have taken advantage of submicrometer GaAs/AlAs+$\delta$-doping/GaAs tunnel junctions previously used for electron gas and impurity spectroscopy [35, 36]. The presence of impurities in the barrier increases the transmission coefficient of the barrier. Due to the small surface of the mesas, the number of impurities involved in the tunneling was very small, of the order of one, and discrete states in the barrier were observed. Under external bias those states were shifted in respect to the quantum well neighboring the barrier, called 'emitter', resulting in current flow. Such a system was exploited to study spin-related effects. In order to create spin polarization, strong magnetic field was applied in the plane of the quantum well, inducing the Zeeman splitting of electron gas states and of the impurity. Both splittings were resolved in the current-voltage-magnetic field maps. The splittings were identified and g-factor for impurity and for quantum well states was evaluated. Moreover, we discovered that in spite impurity assistance in the tunneling process, the spin of tunneling electrons is conserved.

In the following publications we have focused on the studies of the properties of (Ga,Mn)As itself. One can expect that the Mn-Mn interaction, leading to ferromagnetism, will depend on the distance between those atoms. In the work [B3] an impact of hydrostatic pressure on Curie temperature was studied. At that time there was one paper in the literature on (Ga,Mn)As under hydrostatic pressure [37]. The Authors have shown an increase of Tc with pressure, of the order of 2K/GPa. The values of Curie temperatures under pressure were found from maximum of resistivity-versus-temperature evolution. Authors have noticed some problems with results from another method: anomalous Hall effect, which in fact, as can be deduced from PhD thesis of the first Author, yielded rather contrary results [38, Fig. 4.5]. Therefore in our studies we have focused on both methods: resistivity measurement as a function of temperature and Hall voltage measurements as a function of magnetic field, at different temperatures and pressures. The investigations were conducted on two samples with Curie temperatures 85 K and 50 K, both obtained by LT-MBE, with different character of $\rho$(T) dependence. The former was metallic with a pronounced maximum in the r(T) curve, the latter – insulating in character, with a rise of resistance at low temperatures and a hardly resolved maximum. The main experimental finding was that those two samples showed opposite pressure variation of the Curie temperature. For the first one, Tc increased with pressure, for the second one, it decreased. It was the first observation of a decrease of Tc with pressure in the scientific literature. Another important conclusion concerned the methodology. For the first sample, both methods gave identical values of both Curie temperature and its pressure rate. For the second one, neither the value not the pressure trend found by two methods agreed. We have pointed to the drawback of the method basing on $\rho$(T) dependence for insulating samples. This issue was further developed by A. Kwiatkowski and myself in [39].

Pressure dependence of paramagnetic-ferromagnetic phase transition temperature for the typical, metallic sample (with an increase of Tc under pressure) was successfully explained with the RKKY model [23], in which exchange interaction between

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Mn ions is mediated by delocalized valence band holes. The theoretically calculated value of the Curie temperature (Eq.(7)) for the situation under pressure, i.e. taking into account elementary cell volume variation, and resulting concentration variation, exchange interaction and effective mass changes, gave a good, quantitative agreement with the experimental value. Moreover, the first principle calculations [40] gave the same pressure trends as experimentally observed for metallic sample. The behavior of the insulating sample was not accounted for in the model. However, one can get a qualitative picture basing on the localization trends for Mn impurity in III-V compounds. The smaller the lattice constant, the more localized the Mn acceptor is. As discussed by T. Dietl [41], stronger localization leads to lower Curie temperature. Moreover, one should take into account that in the available theoretical approaches [23, 40] a constant concentration of free carriers mediating ferromagnetic interaction is assumed. As we have observed both, an increase and a decrease of Tc for different samples, there are new experiments in progress to verify this assumption.

In paper [B4] we have focused on magnetic properties of ferromagnetic (Ga,Mn)As. Due to the complicated valence band structure in the presence of magnetization, an anisotropy of magnetization is observed. There are certain axes of preferential magnetization alignment, corresponding to a minimum of free energy. An important contribution to magnetic anisotropy comes from the strain in the layer. Glunk et al. performed systematic studies showing the relation between the values of anisotropy constants and epitaxial strain [28]. Those investigations were extended by us [B4] through the results for (Ga,Mn)As layer with extremely high lattice mismatch of 2% (strain $\varepsilon_{zz}$ = –1.8% compared to –0.4%, reported in the literature). Such sample was grown by dr hab. Janusz Sadowski on a In$_{0.3}$Ga0$_{.7}$As buffer. It is worthy to underline that growing such a high quality mismatched structure is a technological feat on its own. Hall effect was measured for different temperatures and magnetization position was determined. Via modeling of free energy, the values of the out-of-plane anisotropy (B$_A$) were obtained. The low temperature value of B$_A$ fits very well to the linear dependence B$_A$($\varepsilon_{zz}$) found by Glunk for $|\varepsilon_{zz}| \leq 0.4\%$. This result shows a wide possibility of out-of-plane anisotropy tuning by a proper buffer engineering. Moreover, the temperature dependence of the anisotropy constant is the same as of magnetization, which reveals an important relation between magnetic anisotropy and magnetization, B$_A$~M [42].

Having established the hydrostatic pressure influence on the Curie temperature, we have undertaken the investigations of Esaki diodes under pressure to verify how the tunneling anisotropic magnetoresistance, reflecting anisotropy of the valence band subbands, is influenced by pressure. The results are presented in [B5]. As valence band is formed with Mn 3d and As 4p states which differ in the localization degree, one could expect some regrouping of those states under pressure. The investigations were performed on junctions with 5.8% Mn content with the Curie temperature of 107 K. The first observation was that the current-voltage characteristics are qualitatively different from the typical Esaki diode characteristics and instead of a negative differential resistance, a biexponential I(V) dependence was observed. However, a careful inspection of the logarithmic derivative of the current-voltage characteristics lead to observation of some traces of band-to-band tunneling, which however was concealed by an excess current. It was related to tunneling with some states present in the gap, most probably related to impurities. We have shown that TAMR effects practically do not depend on pressure for positive bias, whereas a small increase of TAMR was observed for the reverse bias. This is a polarization used for spin injection experiments, when electrons from (Ga,Mn)As valence band tunnel into GaAs conduction band states. As the value of TAMR scales with the degree of spin polarization [43], this results suggest an increase of spin polarization under pressure.

The final publication constituting this scientific achievement is paper [B6]. Basing on publications [B3] and [B4], showing impact of hydrostatic pressure on the Curie temperature and relation between strain and magnetic anisotropy, respectively, an influence of hydrostatic pressure on magnetic anisotropy is investigated. Studies of the out-of-plane and in-plane (cubic and uniaxial) anisotropies were conducted for two samples. In the first one GaMnAs layer was under small compressive epitaxial strain, in the second – under large tensile strain. The evolution of magnetization with temperature and pressure was determined from the anomalous and planar Hall measurements. The values of anisotropy constant were extracted as a function of temperature and hydrostatic pressure up to 1 GPa. To our knowledge, this is the first report on the dependence of anisotropy constants of (Ga,Mn)As on hydrostatic pressure. The studies revealed a general trend of increased magnetic stiffness of (Ga,Mn)As under pressure.
The out-of-plane anisotropy constant increases with pressure, in agreement with the predictions of the Zener model. However, the calculated values of anisotropy constants and their pressure rates are systematically smaller than in the experiment. The cubic and uniaxial anisotropy constants increased by 30% and 20%, respectively at 1GPa in respect to the ambient pressure values. The latter value was referred to the model of bulk uniaxial anisotropy [44], which predicts an anisotropy rise, however much lower than experimentally found.

## 4.4. Summary

The works constituting the scientific achievement focus on the properties of (Ga,Mn)As itself and on the process of tunneling of spin polarized carriers. The tunneling magnetoresistance in GaMnAs was evidenced, both at ambient [B1] and at high hydrostatic pressure [B5]. The conservation of electron spin during tunneling via impurity states was shown [B2]. Magnetic anisotropy of GaMnAs was found in the samples with extreme values of epitaxial strain [B4]. The strain was also tuned with hydrostatic pressure, and thus the impact of pressure on magnetic properties: magnetic anisotropy [B6] and Curie temperature [B5] was found.

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## 5. List of other scientific achievements, not contributing to point 4 above.

### 5.1. before obtaining PhD degree

My scientific activity began with the studies of tunneling effects in the non-magnetic semiconductors, single barrier GaAs/AlAs/GaAs, in particular. It is an interesting system, as the AlAs layer is a quantum well of electrons from the $\Gamma$ point in the Brillouin zone and at the same time a quantum well for electrons from the X minimum. In order to modify the transmission coefficient some samples were $\delta$-doped in the center of the AlAs layer. Large mesas were studied and the average number of donors was about $10^6$ per mesa. Current-voltage characteristics were measured at liquid helium temperature, in magnetic field up to 7 T and under hydrostatic pressure. We have shown the participation of donors in the tunneling, resolved as a strong current increase at a certain bias range present only for the doped samples. The increase was composed of two broad peaks. At higher bias, another group of current peaks was observed, this time present for both reference and doped samples, due to the tunneling through the states of quantum well. Using hydrostatic pressure, we have proven that both quantum well and donor states were related to the X minimum in the Brillouin zone. The donor-related peaks were ascribed to longitudinal (along current/growth direction) and transverse X minima, which due to the epitaxial strain were not equivalent. The investigations have lead to interesting conclusions, that

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high in-plane momentum mismatch between the initial electron state in the reservoir and intermediate state does not prevent the electrons from tunneling.

In subsequent works, tunnel junctions with smaller surfaces were prepared in order to reduce the number of impurities inside the junction and reach the limit of single donors. By means of electron beam lithography and reactive ion etching square mesas with side length from 100 nm to 2μm were prepared. Making top Ohmic contacts to that small mesas proved to be a challenging task. In the current-voltage characteristics, measured at miliKelvin temperatures, structures related to tunneling via discrete energy states were identified [A3]. Furthermore, the observation of the step-like density of states of two dimensional electron gas without magnetic field and the Landau quantization at strong magnetic fields, have shown the tunnel current reflects the density of states of the reservoir. Moreover, the participation of acoustic phonons in the tunneling process was clearly resolved [A4]. Thus, the single donor gave an insight into microscopic properties of the electron gas and of the tunneling process. At that time such studies were rather unique and only after several years did single object spectroscopy bloom as 'solotronics'.

### 5.2. after obtaining PhD degree

After my PhD, I continued the investigations on the tunneling through single impurities. It was shown that with a single donor in the barrier, it was possible to perform a spectroscopy of the carrier gas in the reservoir from which they tunnel [A5]. A single Si donor in AlAs, due to its small Bohr radius (~5 Å) is a very local probe of electron state density and thus small disorder-induced fluctuations of the local density of states were successfully resolved. This enabled the identification of the excited states of the same dopant [A6], as recently confirmed by calculations (A. Twardowska – Ph.D. thesis, in preparation). Furthermore, Landau levels in the reservoir quantum well were observed with fine current peaks superimposed on them. By following their magnetic field and polarization evolution, using modeling of energy states in a parabolic quantum well with the disorder, we were able to attribute them to the disorder.

Another area of my work was related to studies of the properties of graphene [A7]. After the exciting reports on the properties of graphene exfoliated using a 'scotch' tape (awarded the Nobel Prize in 2010), the Institute of Electronic Materials Technology (ITME) in Warsaw initiated the fabrication of graphene samples using first SiC sublimation and subsequently CVD methods. Hall effect measurements were performed on the sublimation-grown samples containing several layers of graphene and the resistivity tensor was determined. The two-dimensional conductivity character of the samples was confirmed. Moreover, it was shown that conductivity is multi-channel one with the mobility in the highest mobility channel being around 8000 $cm^2/Vs$. In subsequent works on CVD-grown mono- and bi-layer graphene, discrepancies between the Hall concentration and that from quantum oscillations of magnetoresistance (Shubnikov-de Haas effect) or of the Hall voltage. It was shown that the concentration found from the low field Hall effect is misleading when the sample contains more than one layer of graphene. The results were confirmed by capacitance measurements bringing independent insight in the structure of the sample. The report on these works in currently in preparation.

I also ventured back to the works performed during my masters to study the behavior of momentum in the tunneling process. As mentioned above in pt. 5.1., two maxima were observed in the current-voltage characteristics, related to tunneling through donor-related states. Their number is related to the nonequivalence of the three X-valleys in AlAs in the structure grown along the [100] direction. New GaAs/AlAs/GaAs tunnel structures were discussed and prepared, grown along the [111] direction with microscopic

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mesas processed. In such a samples the three X-minima are equivalent. The studies of these samples revealed the presence of one maximum in the current voltage characteristics in the voltage range at which tunneling through the donor levels was observed. Again, the observation of the transition with a significant mismatch of the transverse momentum has to be related to the presence of another quasiparticle in the tunneling process.

Finally, I participated in a number of (Ga,Mn)As studies, that are not included in the scientific accomplishment due to my small contribution. One work [A10] was related to the observation and explanation of the origin of structures observed in longitudinal and transverse resistivities as a function of the magnetic field in Hall-bar structures fabricated in thin (Ga,Mn)As films. The propagation of the magnetic domain along the Hall-bar induces the local change in the resistivity tensor, detected by the voltage probes. The second work [A11] is a development of the problem mentioned in p. 4.3. concerning the methodology of $T_C$ determination for insulating (Ga,Mn)As samples. The determination of Tc from the maximum of $\rho$(T) was earlier questioned by V. Novak et al. (prof. T. Jungwirth's group in Prague) who showed that the maximum of the $d\rho/dT$ gives the proper $T_C$ value. In the work [A11] it was shown that this approach cannot be used universally and in particular in the case of insulating samples it does not work. Other means of $T_C$ determination were proposed, based on transport measurements.

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