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ANALYSIS OF THE ELECTRICAL, MAGNETIC AND STRUCTURAL PROPERTIES OF A_3B_6 TYPE LAYERED SEMICONDUCTOR CRYSTALS INTERCALATED WITH METALS WITH REFERENCE TO THEIR MILITARY APPLICATIONS

Magnetic sensors are key elements in many security and military systems. Magnetic sensors are often used for military applications such as navigation, position tracking and antitheft systems. Nowadays sensitive magnetic sensors are used in many technical systems, including modern anti-tank missiles to identify the center of the target area and a minimal armor region.

The applications of magnetoresistive structures based on semiconductor crystals of InSe for high precision measurement of the magnetic field are outlined in this article. Possibilities of using magnetic field sensors based on InSe structures for revealing the armour military vehicles are discussed. The impact of metal impurities on the layered structure of the semiconductor material as referred to the strong covalent bond within the layers as well as the weak van-der-Waals bond in the interlayer space is studied. Nyquist diagrams for InSe crystal with the impurities of nickel at different temperatures ranging from liquid nitrogen to room temperature are analyzed. Temperature is shown to be a significant factor for affecting the Nyquist diagrams. The curvature of the Nyquist diagrams for intercalated InSe varies with the temperature as opposed to the pure InSe. Topological images of crystal surface obtained by using atomic force microscopy confirmed the layer structure of nickel-intercalated InSe. Structures with alternating layers of semiconductor and metal provide the fundamental control of magnetic properties. These structures have a sharp anisotropy of magnetic susceptibility. The investigated semiconductor crystals with impurities of 3d-elements can extend the functionality of modern magnetic sensors designed to detect heavy armor.

Keywords: *layered semiconductor, impedance, Nyquist diagrams, intercalation.*

Introduction

Magnetic sensors are often used for security and military applications such as detection, discrimination and localization of ferromagnetic and conducting objects, navigation, position tracking and antitheft systems [1].

Magnetic sensors are key elements in many security and military systems. Traditional sensors such as fluxgates, induction coils and resonance magnetometers are complemented by new sensor types such as AMR (Anisotropic MagnetoResistors), GMR (Giant Magneto-Resistance), SDT (Spin-Dependent Tunelling) and GMI (Giant Magneto-Impedance) sensors [2].

Analysis of recent research and publications

InSe is a typical layered semiconductor material from A_3B_6 group, that can be used for optical detectors in visible and near infrared spectrum region. In quantum electronics these structures can be used for the creation of the high- efficient photovoltaic converters, gas sensors and thermoelectric transducer, as well as the effective THz laser radiation sources [3].

InSe structure is characterized by the fact that it can be viewed as quasi two-dimensional (2D) [1]. In-Se atoms form layers with strong covalent bond, while interlayer space is filled with a weak Van der Waals bond, so processes across the layers can be viewed as a perturbation to the ones along the layers. This leads to strong anisotropy of the properties of these structures [4,5].

The discovery of single-atomic layer graphene [6] has led to a surge of interest in other anisotropic crystals with strong in-plane bonds and weak, van der Waals-like, inter-layer coupling. A variety of two-dimensional (2D) crystals with high crystalline quality and stable properties under ambient conditions have been investigated recently. Interest in these systems is motivated partly by the possibility of combining them with graphene to create 2D electronic devices, e.g., field effect transistors with high on-off switching ratios and memory cells [7].

In recent work these materials were shown to possess magnetoresistive properties and were proved to be useful for magnetic sensors [4, 5, 8, 9].

Magnetoresistive structures can not only provide a Coulomb blockade of the electric current, but also create conditions for the emergence of new unique magnetic properties that serve as the basis for new approaches to technology issues – information carriers. In particular, the giant magnetoresistive effect in nanostructures with alternating semiconductor and metal layers offers the prospect of a radical restructuring of materials technology – development of information carriers and the creation of highly effective quantum computers.

Nowadays sensitive magnetic sensors are used in many technical systems, including modern anti-tank missiles to identify the center of the target area and a minimal armor region. Materials based on magnetoresistive structures are resistant to extreme temperatures, and ionizing radiation, so they are promising for use in guidance systems of modern microprocessor warheads [10].

Basic statements. Magnetic sensors numerically register these perturbations (anomalies) of the background magnetic field of the Earth, and modern methods of digital processing of analog signals allow a relatively accurate determination of the mass, direction and speed of the above mentioned objects [10]. Over the past 30 years magnetoresistive structures boost their share role on sensor technology sector of the market of weaponary.

Magnetoresistive structures – objects that have the ability to alter their current-voltage characteristics depending on changes in the external magnetic field. Sensors based on magneto-resistive structures are highly sensitive to the magnetic field fluctuations (10^{-15}T at temperatures of liquid helium, and 10^{-13}T at room temperature) [11]. This property is used in a wide field of military technologies, such as: navigation, detection of submarines, missile guidance to the target, etc.

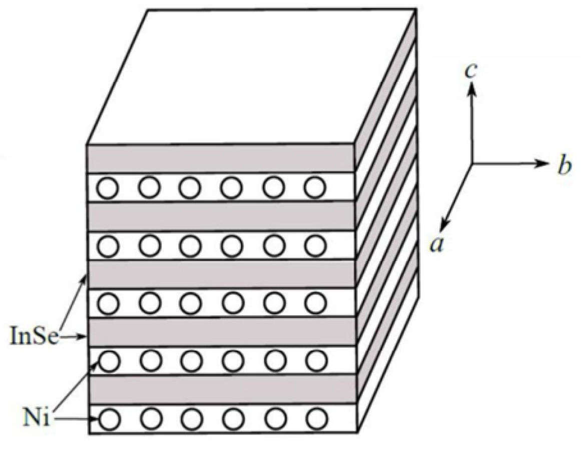

Fig. 1. **InSe structure (*a*=*b*=4,002 Å, *c*=24,946 Å) intercalated with Ni**

InSe is one of the materials susceptible to a giant magneto resistive effect [12] which makes it useful for magnetic sensors.

The explanation of this phenomenon is based on a quantum-mechanical theory and is throroughly described in [12].

The purpose of the article. 1) To investigate the dependence of real and imaginary components of the resistivity of Ni_xInSe structure (Fig. 1) as a function of temperatures and nickel content x. 2) To analyze the impact of metallic impurity, its concentration and temperature on the electrical, magnetic and structural properties of InSe.

Presenting main material. The unique possibilities of change of the ferromagnetic properties of a hybrid system ferromagnetic-semiconductor by the optical and electrical methods cause today heightened interest [13]. Such changes may be used, in particular, at making of the modern functional units of spintronics. As the effect of the influence of semiconductor on a ferromagnetic is more marked for the thin ferromagnetic film there is actual a problem of reception of the semiconductor structures with minimally possible thickness alternating magnetoactive layers [14].

Introduction (intercalation) of different by their properties foreign atoms, in particular metallic atoms of the iron transition group into the structure of the layered crystal expands the range of new compounds with unique properties. The appearance of even a small concentration of magnetic impurities in the InSe crystal may significantly affect the electrical, magnetic and optical properties of the crystal. Lattice, in its turn, will affect the magnetic moment of the intercalant leading to anomalous kinetic and magnetic properties of such structures [15].

For example, the introduction of the element of 3d-iron group in the $TiSe_2$ matrix leads to the formation of Ti-M-Ti covalent centers. In the case of M_xTiSe_2, (where M - metal atoms of Ni, Co, Ag) intercalation is accompanied by a decrease in the lattice constant along the anisotropy axis [16].

The covalent centers of In-M-In in the Ni_xInSe structure can act as traps for free charge carriers, on the one hand, and as centers of lattice distortion on the other. Since the introduction of metal atoms of 3d-iron group into the matrix of the layered semiconductor crystals significantly affects their properties, the magnetization can be assumed to be an important factor regulating the above mentioned effects under the influence of an external magnetic field [15, 16]. The influence of metal atoms of 3d-iron group on the matrix of semiconductor layered crystals was studied in details in [4]. Some peculiarities of the behavior of In_4Se_3 doped by metallic impurities have been discussed in [5, 8, 9]. Impedance spectroscopy measurements in the frequency range of $10^{-3} \div 10^{6}$ Hz were carried out using a measuring complex "AUTOLAB" by the company "ECO CHEMIE".

To investigate the effect of metallic impurities on the layered InSe structure the dependences of the imaginary impedance component as a function of real one for: 1) pure InSe; 2) InSe with Ni (3%); and 3) InSe with Ni (5%) are outlined in the Figures below.

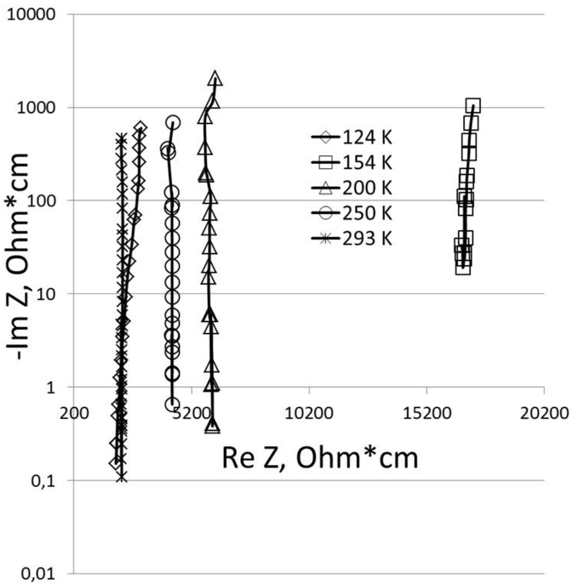

Fig. 2. **Nyquist diagrams for pure InSe at different temperatures**

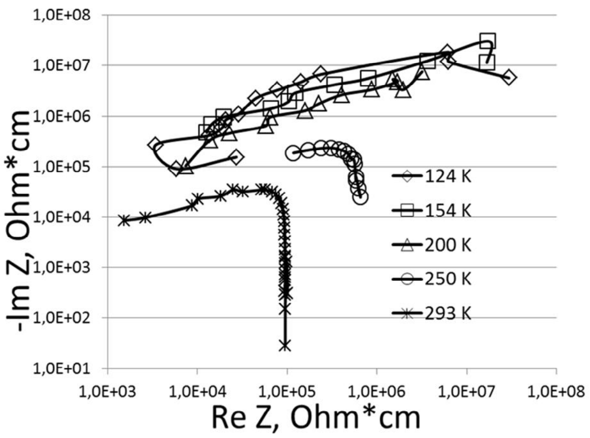

Fig. 3. **Nyquist diagrams for InSe with Ni (3%) at different temperatures**

To analyze the layered structure of InSe the topological images of pure InSe surface were captured by using atomic force microscope (AFM) Solver P47 PRO (NT-MDT). The measurements have been done in contact mode using Si-type cantilevers with a tip rounding radius of 10 nm.

The primitive unit cell of rhombohedral γ-InSe along the c-axis contains three layers, each consisting of four monoatomic sheets of hexagonally arranged atoms linked in the sequence Se-In-In-Se via covalent bonds. In crystal, these individual InSe layers are held together by van der Waals forces [7].

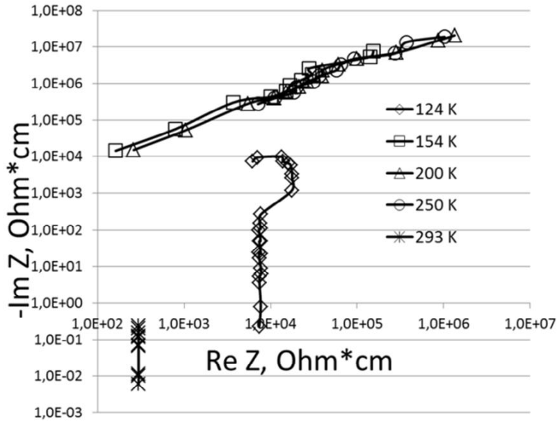

Fig. 4. **Nyquist diagrams for InSe with Ni (5%) at different temperatures**

In Fig. 5 the obtained 3D image of InSe surface is shown which is formed by wide terraces of uniform thickness. According to the lattice parameter *c* = 24.961 Å it can be concluded that these thick terraces consist of several tens of layers. As it can be noticed, the cleaved facets of InSe layered crystals are very smooth and contain a low-density of surface defects.

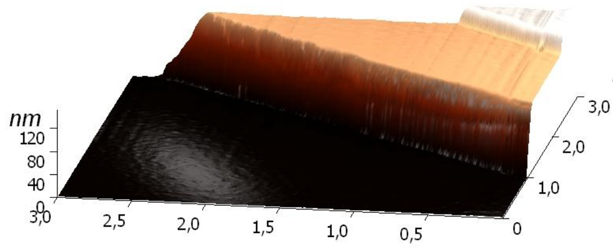

Fig. 5. **3D AFM image of InSe layered structure**

In Fig. 6 the 3D image of thinnest observed terrace is presented which corresponds to single layer of InSe.

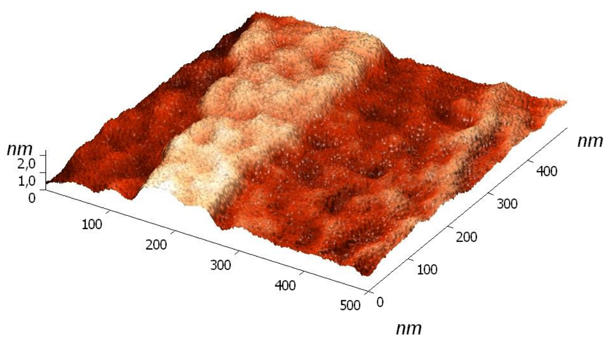

Fig. 6. **3D AFM image of InSe single layer**

In order to determinate the thickness of InSe single layer the histogram height plot was built (Fig. 7) which shows the distribution of height from all the points over the acquired surface.

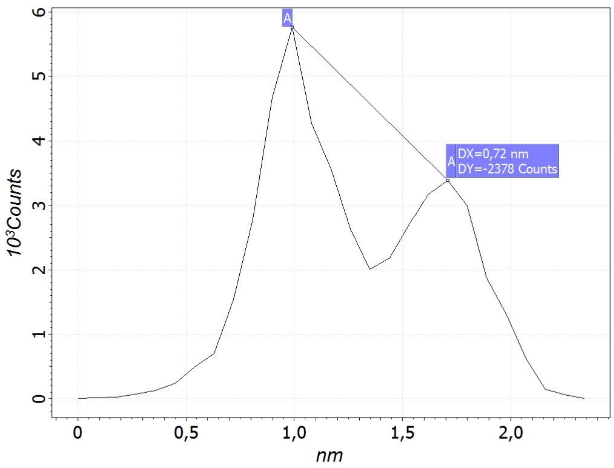

Fig. 7. **The histogram height plot from which the single layer InSe thickness was determined**

The experimental value of the thickness of InSe single layer was statistically found to be about 0.7 nm which is approximately one third of the *c* lattice parameter consisting of three such layers.

Conclusions

The values of Re Z and Im Z for intercalated InSe are considerably higher than that ones for the pure InSe. Temperature is shown to be a significant factor for affecting the Nyquist diagrams. The curvature of Nyquist diagrams for intercalated InSe varies with temperature as opposed to the pure InSe. This may be due to the traps for charge carriers introduced introduced by the guest Ni which makes Re Z susceptible of the frequency change. AFM images of pure InSe confirm its layered structure with the obtained single layer thickness of about 0.7 nm.

Structures with alternating layers of semiconductor and metal provide the fundamental possibility to control the magnetic properties. These structures have sharp anisotropy of magnetic susceptibility. The investigated semiconductor crystals with impurities of 3d-elements can extend the functionality of modern magnetic sensors designed to detect heavy armor.

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Аналіз електричних та магнітних властивостей шаруватих напівпровідникових кристалів типу $a_3в_6$, інтеркальованих металами з огляду на їх військове застосування

Б.О. Середюк, Ф.О. Іващишин, Б.Я. Кулик

У статті виконаний аналіз перспектив застосування магніторезистивних структур на основі напівпровідникових кристалів типу InSe для прецизійного вимірювання магнітного поля. Розглянуто можливість застосування сенсорів магнітного поля на основі структури InSe для виявлення військової бронетехніки. Досліджено вплив домішок металів на шарувату структуру напівпровідникового матеріалу як на сильний ковалентний зв'язок всередині шару, так і на слабкий Ван-дер-Ваальсовий зв'язок у міжшаровому просторі. Проаналізовано діаграми Найквиста для кристалу InSe, з домішками нікелю при різних температурах від кімнатної до температури рідкого азоту. Топологічні знімки поверхонь InSe, використовуючи методику атомно силової спектроскопії, підтверджують його шарувату структуру.

Ключові слова: *шаруватий напівпровідник, імпеданс, діаграми Найквіста, інтеркаляція.*

Анализ электрических и магнитных свойств слоистых полупроводниковых кристаллов типа $a_3в_6$ интеркалированных металлами с точки зрения их военного применения

Б.А. Середюк, Ф.О. Иващишин, Б.Я. Кулык

В статье выполнен анализ перспектив применения магниторезистивных структур на основе полупроводниковых кристаллов типа InSe для прецизионного измерения магнитного поля. Рассмотрена возможность применения сенсоров магнитного поля на основе структуры InSe для обнаружения военной бронетехники. Исследовано влияние примесей металлов на слоистую структуру полупроводникового материала как на сильную ковалентную связь внутри слоя, так и на слабую Ван-дер-Ваальсовую связь в межслоевом пространстве. Проанализированы диаграммы Найквиста для кристалла InSe с примесями никеля при различных температурах от комнатной до температуры жидкого азота. Топологические снимки поверхностей InSe, используя методику атомно силовой спектроскопии, подтверждают его слоистую структуру.

Ключевые слова: *слоистый полупроводник, импеданс, диаграммы Найквиста, интеркаляция.*

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ВПЛИВ ВІТРУ НА ЗОВНІШНЮ БАЛІСТИКУ КУЛІ, ВИПУЩЕНОЇ ІЗ СВД

У роботі розглядається динаміка руху кулі у повітрі, випущеної із снайперської гвинтівки Драгунова. Вважається, що на неї діють сила лобового опору повітря, вага кулі та сила, спричинена дією бічного вітру. Сила лобового опору повітря залежить від коефіцієнта аеродинамічності, площі поперечного перерізу кулі, густини і швидкості звуку в повітрі, швидкості супутнього або зустрічного вітру, швидкості кулі та двох безрозмірних коефіцієнтів, які мають різні значення при надзвуковій і дозвуковій швидкостях кулі. Величина сили, обумовленої дією бічного вітру, пропорційна максимальній площі повздовжнього перерізу кулі, густині повітря та різниці швидкостей вітру і бічного зміщення кулі, яка піднесена до певного ступеня. Між теоретичними та експериментальними результатами кінематичних параметрів кулі досягнута незначна розбіжність. Однак при дії бічного вітру є значні розбіжності, якщо координата точки обнуління траєкторії понад 700 метрів. Проведенням теоретичної перевірки експериментальних значень встановлено, що на окремих ділянках руху кулі значення середньої швидкості її бічного зміщення суперечить законам механіки.

Ключові слова: *зовнішня балістика кулі, сила лобового опору повітря, вплив вітру.*