Obtaining and Investigation of Pb\(_{1-x}\)Mn\(_x\)Te(Se, S) Semimagnetic Semiconductor Nanolayers Sensitive to Infrared Rays

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Abstract: - In the given work the energy spectrum and wave functions have been theoretically calculated for quantum-sized films of Pb\(_{1-x}\)Mn\(_x\)Te(Se, S) semimagnetic semiconductors. The photo- and electroluminescence properties of Pb\(_{1-x}\)Mn\(_x\)Te(Se, S) thin films by the mathematically modeled method of molecular beams epitaxial on BaF\(_2\) substrates were studied. It was established that band gap width of epitaxial layers expanded by the change in Mn amount.

Key-Words: - semimagnetic semiconductor, nanolayer, sensitive, detector, infrared, electroluminescence, photoluminescence, energy spectrum.

1 Introduction

Today, IR technology widely intrudes into all spheres of our life. So, modern devices make it possible to follow volcano activity, to inform about oncoming tsunami, to record other signs of nature activity, which is invisible to human eye.

IR detectors play an important role in our life. They have a lot of application fields: defense-industrial sector, science, industry, medicine, and security. It is the receiver of radiation energy, which converts IR energy to a measurable form. IR detectors detect the energy, radiated from objects, then the uncovered energy is transformed to the image, which shows the difference in objects’ energy, and in this way they all become visible.

IR thermograph – the method of recording IR radiation from human body surface. It is a unique wide range method of diagnostics and control method of patient’s status in the case of abnormalities of wide range. This method is applied in oncology for differential tumor diagnostics. It is a secure, reproducible method, which does not make any way for other diagnostic methods on sensitivity and specificity. Depending on rise or decrease of local temperature on the phone of habitual profile of organ or extremities, become stronger or on the contrary weakens weavings glow in pathology field. Thermal imaging method is notable for absolute security, simplicity and rapid examination, lack of any contraindication.

IR detectors: movements, magnetocontact, radial, perturbed buttons are used for any control of access, perimeter, guarded and not guarded objects (house, farm, campsite, storehouse, oil storages and etc).

IR – passive transducer, also called optoelectronic, concern to the movement detector class and react to thermal radiation of moving body. Mechanism of these transducers is based on the record of time change differences between IR radiation intensity from human and background thermal radiation. Nowadays IR-passive transducers are very popular; they present an integral element of guard system practically of each object.

IR transducers – perimeter conservation create an invisible fence around our yards. Transmitters and detectors are settled opposite of each other along the whole perimeter of the yard. It creates a barrier of IR rays and signal is transmitted at discontinuity of such ray on control panel in order to take appropriate measures.

Today the pyrometer is relatively an inexpensive noncontact method of temperature measuring. The mechanism of pyrometer is based on the measuring the absolute value of IR radiation of the researched object. Pyrometers are able to be induced on object from any distance; their capabilities are restricted only with diameter of measured spots and environment transparency. Pyrometers are ideal for portable models. Modern sensing technology enables to perform the pyrometer without moving elements, and in this way it ensures great longevity for the pyrometer. Besides this, such kind of pyrometers is notable for its high electromagnetic noise immunity and measurement accuracy (an up-to-the-minute processing technology, digital...
multpoint linearization). They are applied for lens system of special structure, which ensure color correction both visible and IR radiation.

We are surrounded with various electric and electronic facilities, devices and equipments, wherever we are. They solve lots of daily problems, facilitate our life, and make it comfortable and pleasant. These facilities are developed day by day, by becoming more complicated system, but reserving special unique property – simplicity in utilization and consumer comfort. Majority of these electronic systems help us not only in creating comfort, watching over our health, ensuring safety, but also considerably saving facilities.

Energy-saving technology did not by-pass the house lighting system, also door intercommunication system and surveillance cameras. IR-passive transducers belong to movement detectors class and react to thermal radiation of moving body. Transducer, which reacts to movement, can control not only room lighting, but also it can be connected practically to any electric apparatus, which is essential for us, in entering into any room. Therefore, IR movement transducer is very convenient for energy and expenses saving, related to its consumption. Besides this, the light regulator is widely used, which enables us not just to switch on/off the light, but also to regulate its intensity.

Today, the majority of fuel and mineral kinds and alternative energy sources have become an integral part of our daily life and production. These inexpensive energy sources and objects bring people comfort and convenience on one hand, but at the same time – a big threat in moderate treatment (not following fire safety measures). Fire-alarm box detectors, which are performed by using the most widespread technologies for today, are used for detection of different explosive and toxic gas concentrations, which practically all of us have met in our life, the effects connected with them: temperature, gas, smoke.

IR currency detector defines the currency authenticity. An image, special invisible to naked eye – so called element “M” is displayed on bank notes In IR rays, which is the proof to the authenticity.

Water leak detectors react to the presence of water, door detectors to the open doors, broken glass detectors are settled on the glass doors and windows, and record the broken glass.

The experience of instrumental researches enables to assume the existence of life mode in plasma state beyond the bounds of our physical nature. These life modes are able to move from one density degree into another, from invisible spectral region to full physical density, which can be observed visually, without any devices. The photos, taken from the airplane, showed that glowing in IR-spectrum or dark invisible objects fly nearby or directly behind the airplanes. For detecting UFO in invisible spectral region, reasonably to use the devices for noctovision in two-stage execution or by image intensifier, which sensitivity enables to detect the object in IR spectral region with enough optical resolution.

All these make a big interest to various detectors, put on the world market. Increased demands for new generation of IR detectors, which overbalance its analogs on sensitivity and effectiveness of IR rays record, for spatial resolution and fast-acting, for lack of hygroscopicity, for availability in extreme climate conditions (temperature stability, high radiation field) come up by developing and creating a new generation of highly-sensitive, fast-acting, radiation-resistant devices (as well as for optoelectronics, industry, cosmic researches in extreme conditions, in instrument engineering, in medicine). Therefore, the investigation on search and development of new IR detectors, which exceed its analogs on physical parameters, came to the first plan. Some crystals, for example, Pb$_{1-x}$MnxTe(Se,S) SMS possess heightened chemical stability and radiational resistance, fast response, sensitivity to IR spectral region. Epitaxial layers of these semiconductors are of special interest in optoelectronics from the standpoint of small-size and optimization of some physical parameters. The development of the technology of obtaining highly sensitive, radiation resistant Pb$_{1-x}$MnxTe(Se,S) SMS nanolayers is considered very expedient for the purpose of development and formation of IR devices with optimal parameters on their base.

Pb$_{1-x}$MnxTe(Se,S) SMS epitaxial layers have a special place among great variety of produced materials. These crystals have perspective to be applied in semiconductor instrument making as photodetectors, photoreceivers. Pb$_{1-x}$MnxTe nanofilms have been the object of researches of many scientists in last ten years.

Previously, it has been worked out the method of obtaining Pb$_{1-x}$MnxTe(Se,S) nanofilms, and their physical properties have been researched in [1]. The authors obtain Pb$_{1-x}$MnxTe epitaxial layers, and research their physical properties, also influence of γ-radiation influence to their properties with the purpose of obtaining radiation resistant and perfect crystals. In the magnetic field it is observed interesting effects qualitative of other character. The energetic structure and interband Faraday effect in
SMS Pb$_{1-x}$Mn$_x$Te nanofilms has been theoretically studied by [2].

The aim of the work is investigation of Pb$_{1-x}$Mn$_x$Te(Se,S) SMS nanolayers to obtain their optimum and perfect samples with high sensitivity and radiation resistance.

I. Energy spectrum and wave functions

In the given work the energy spectrum and wave functions have been theoretically calculated for quantum-sized films of Pb$_{1-x}$Mn$_x$Te(Se,S) SMS. The properties of the electrons and holes in the exchange semiconductors IV-VI are described by Dimmock model [3]. But at the energies $E \leq E_g$, where $E_g$-band gap can be limited by a double-band model, as in this case Dimmock model doesn’t lead to qualitatively new results [4]. For the calculation of the spectra and wave functions double-band Kane model has been used. The $\kappa_z=0$ case is considered.

Let’s assume that the surface of the film is perpendicular to the axis $x$. In the model of rectangular wells with infinite walls in the double-band approximation, when the spin-spin exchange interaction occurs between the electrons in the conductivity band (valence band) and the electrons of half-filled d-shells of manganese ions as well as taking into account electron spins and the band nonparabolicity we have:

$$E_{jn_\|} = -\frac{E_g}{2} + \frac{2}{3} \mu H + \frac{\alpha}{2} - \frac{\beta}{2}$$

(1)

$$\sqrt{E_{jn_\|} - \frac{2}{3} \mu H + \frac{\alpha}{2} + \frac{\beta}{2}}^2 + P_{\perp}^2 k_{\perp}^2 + P_{\perp}^2 \alpha^2$$

$$\psi_{j\sigma_j n_j k_z}(r_z, x) = \frac{2}{\sqrt{S_d}} \left( A_{j\sigma_j n_j k_z}(r_z, x) \sin \alpha x + B_{j\sigma_j n_j k_z}(r_z, x) \cos \alpha x \right) e^{i k_z z}$$

(2)

$$A_{jn_\| k_z}(r_z, x) = L_{jn_\| l}(U_d - U_g - \frac{i P_{\perp} k_{\perp}}{E_{jn_\|} + E_g - \mu H - \alpha})$$

(3)

$$B_{jn_\| k_z}(r_z, x) = -L_{jn_\| l}(U_d + \frac{P_{\perp} \alpha_j}{E_{jn_\|} + E_g - \mu H - \alpha})$$

$$E_{jn_\| k_z} = -L_{jn_\| l} U_d + \frac{P_{\perp} \alpha_j}{E_{jn_\|} + E_g - \mu H + \alpha}$$

(4)

where $\alpha_j = \pi n_j / d$, $S_\pm = \pm 1$ spin-up and spin-down states, $E_g$ band gap, $j = c, v$. $P$ - is the Kane constant.

$A = \frac{1}{2} N_\sigma \alpha (S_\sigma)$, $B = \frac{1}{2} N_\sigma \beta (S_\sigma)$

Are exchange parameters, arrows indicate the spin state.

3. Photo- and electroluminescence spectra

In the present work the dependence of band gap on Pb$_{1-x}$Mn$_x$Se thin films’ composition was determined out of photoluminescence spectra. The magnitude of exchange interaction was estimated in magnetic field due to the experiments on photo-and electroluminescence for Pb$_{1-x}$Mn$_x$Te(Se,S) crystals.

The structural perfection of the films was controlled by electronographic, electromicroscopic and X-ray diffraction methods. Epitaxial films were grown by the mathematically modeled method of molecular beam condensation in vacuum $10^{-4}$ Pa.

Optimal conditions ($\nu_b=8+9$ Å/sec; $T_c=663+673$ K) of manufacturing epitaxial films with a perfect crystal structure ($W_{1/2}=80+100^{\circ}$), growth plane (111), lattice parameter $a=6.10+6.05$ Å and charge carrier mobility $\mu_{77K}=2.53-10^4$ cm$^2$/V·sec were determined.

It was established that structurally perfect Pb$_{1-x}$Mn$_x$Se films with different (n,p) conduction types and specified electrophysical properties can be
obtained by regulating the temperature of compensating Se source.

As far as we know, it’s necessary to manufacture films with a clean and smooth surface without switching the second phase for making various photosensitive epitaxial structures. For this purpose additional compensating source Se was used in the process of film growth. The application of this source resulted in manufacturing Pb\(_{1-x}\)Mn\(_x\)Se films with a clean and smooth surface without switching the second phase.

Photoluminescence excitation was realized by an impulse YAG laser (\(h\nu_0\approx 1.17\) eV). Pumping intensity equaled to \(10^5\) W/cm\(^2\). The measurement was carried out on reflection geometry at 77.4 K. The magnetic field was parallel to a crystallographic direction [100]. Radiation spectra were recorded with the help of a lattice monochromator and two radiation detectors on Ge\(\langle\text{Au}\rangle\) and Ge\(\langle\text{Cu}\rangle\) base. Band gap \(E_g\) was determined along the long-wave edge of radiation spectra. The accuracy of \(E_g\) determination depended on a concrete sample and equaled to 0.1÷0.2%. Within energy region of 0.15 eV where magnitooptical measurements were carried out spectral resolution was 0.15÷ 0.20 MeV. High spectral resolution allowed observing material heterogeneity according to the composition (up to \(\Delta x\approx 10^{-4}\)) as well as luminescence intensity during scanning on the sample surface. The regions with maximal photoluminescence intensity were selected for conducting measurements.

In fig.1 the dependence of radiation quantum energy on the compositions of three thin films - Pb\(_{1-x}\)Mn\(_x\)S (0\(\leq\)x\(\leq\)0.04), Pb\(_{1-x}\)Mn\(_x\)Se (0\(\leq\)x\(\leq\)0.04) was shown. It becomes evident that the dependence \(E_g(x)\) can be considered linear one in the given region. The inclination \(dE_g/dx\) is practically the same at 77 K temperature and equals to 3.2, 3.4 and 3.8 eV/fraction \(x\) correspondingly for Pb\(_{1-x}\)Mn\(_x\)S, Pb\(_{1-x}\)Mn\(_x\)Te, Pb\(_{1-x}\)Mn\(_x\)Se. For two samples with high manganese (Mn) composition - Pb\(_{0.95}\)Mn\(_{0.05}\)Te, Pb\(_{0.96}\)Mn\(_{0.04}\)Se the radiation quantum energy was considerably lower (correspondingly 273 and 267 MeV at 77 K) than appropriate linear inclination values \(dE_g/dx\).

4 Conclusion

It should be mentioned that radiation quantum energy for binary crystals (without manganese) grown by Bridgman method is more than band gap energy measured on qualitative epitaxial layers with charge carrier concentration of \(\sim 10^{17}\) cm\(^{-3}\). In dependence with the sample, charge carrier concentration and excitation level this difference reaches \(\sim 10\) MeV.

In connection high excitation level is required which leads to Burstein shift and crystal heating, i.e. to radiation quantum energy increase. It means that conservative values \(E_g\) (within 10 MeV) are acquired for Bridgman crystals with manganese (Mn). However, it has weak effect on inclination magnitudes [5-7].

During manganese introduction the number of the observed transitions obviously decreases due to low radiation quantum yield of the material. Thereby, during Mn introduction into A\(^{IV}\)B\(^{VI}\) type semiconductor the band gap rises with \(x\) growth, and at low values \(x(x\leq 0.02)\) this dependence becomes linear. Besides, Mn introduction violates mirror symmetry of energy bands in magnetic field because of the fact that the contribution of exchange interaction to \(g\)-factor is more for holes than for electrons. It’s necessary to use epitaxial layers for carrying out more accurate photoluminescence measurements, as Bridgman crystals have low radiation quantum yield and considerable composition heterogeneity.

References:


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