Technical Physics Letters, 2022, Vol. 48, No. 13

07

Circularly polarized electroluminescence at room temperature in heterostructures based on GaAs:Fe diluted magnetic semiconductor

© M.V. Ved, M.V. Dorokhin, V.P. Lesnikov, A.V. Kudrin, P.B. Demina, A.V. Zdoroveyshchev, Yu.A. Danilov

Research Institute for Physics and Technology, Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, Russia
E-mail: mikhail28ved@gmail.com

Received April 19, 2021
revised July 9, 2021
accepted July 13, 2021

In this work, we demonstrate the possibility of using a diluted magnetic semiconductor GaAs:Fe as a ferromagnetic injector in a spin light-emitting diode based on a GaAs/InGaAs quantum well heterostructure. It is shown that in such a device it is possible to observe partially circularly polarized electroluminescence at room temperature.

Keywords: spin light-emitting diodes, diluted magnetic semiconductors, A3B5 semiconductors, spin injection.

DOI: 10.21883/TPL.2022.13.53370.18836

Light-emitting diodes with circular polarization of electroluminescence controlled by magnetic field (spin light-emitting diodes) are considered to be prospective components of the modern optoelectronics due to the possibility of coding the optical radiation by means of its polarization. The building-up principles of such light sources have been actively developed since the 2000s [1–3]. The main achievements are related to obtaining ferromagnetic metal/semiconductor heterostructures where multilayer structures based on ferromagnetic metals are used to inject spin-polarized electrons into a semiconductor structure [4]. In this case the design of spin light-emitting diodes (LED) is strictly limited by peculiarities of the ferromagnetic metal/semiconductor contact [1,2,5]. Spin LEDs based on diluted magnetic semiconductors (DMS) demonstrate much higher functional flexibility [5]. These are materials where magnetic and semiconducting properties are combined due to doping with magnetic impurities (3*d*-transition metals) [3]. The main advantage of these materials is their compatibility with currently functioning semiconductor technologies [5]. On the other hand, the main drawback of most diluted magnetic semiconductors is their low Curie temperature, which significantly limits their use at the present time. Most studied DMS at the moment is GaAs:Mn. This material has ferromagnetic properties at temperatures of up to 200 K, which means that the operating temperature of spintronic devices based on it will also be below 200 K [6]. Based on this, the problem of increasing the Curie temperature of diluted magnetic semiconductors is one of the most relevant in the field of spin light-emitting diode technology. In the last few years active research is being focused on A^3B^5 materials doped with Fe atoms to obtain a DMS of A^3B^5:Fe type. Thus, in [7], the method of molecular beam epitaxy was used to grow thin layers of InSb:Fe diluted magnetic semiconductor with Fe content of 16%; it was shown that Curie temperature of this material exceeds 300 K. In [8], ferromagnetic layers of GaAs:Fe with Fe content equal to 20% were obtained where Curie temperature exceeds 300 K as well.

This work reports on the creation and research of emitting properties of a spin LED where a ferromagnetic layer of GaAs:Fe was embedded in a structure as an injector of spin-polarized carriers. The emission of circular-polarized electroluminescence (EL) in the GaAs:Fe/MgO/GaAs structure was demonstrated.

The sample under study was produced in several stages. At the first stage, the semiconductor part of the structure was formed by the method of vapor-phase epitaxy from metal-organic compounds in a stream of hydrogen at atmospheric pressure and a temperature of 600°C. On the *p*-GaAs substrate, the following layers were successively grown: *p*-GaAs buffer layer, $In_{0.2}Ga_{0.8}As$ quantum well layer, *i*-GaAs spacer layer (with a thickness of 120 nm). In the middle of the *i*-GaAs spacer layer there is a δ-doped Si layer. Earlier in [9] it was shown that when growing heterostructures of A^3B^5:Fe/GaAs type by the method of pulsed laser deposition, the EL is strongly affected by properties of the heterointerface, and the application of a protective layer of MgO dielectric between GaAs and A^3B^5:Fe contributes to improvement of the interface quality. With this in mind, in this study a protective layer of MgO with a thickness of 1 nm was also applied on the formed heterostructure by the method of electron beam vapor deposition. At the next stage, the method of pulsed laser deposition was used to form the layer GaAs:Fe with a thickness of 40 nm with iron content of 20% at a temperature of 200°C. Thickness of the layers was defined by the time of the growing process, taking into account the known deposition rate. The deposition rate for layers of GaAs:Fe type was determined earlier in [8]. Concentration of Fe was also determined by the process parameter, that is the ratio between scattering times of GaAs and Fe targets ($Y_{Fe} = t_{Fe}/(t_{Fe} + t_{GaAs})$), where t_{Fe} and t_{GaAs} are the

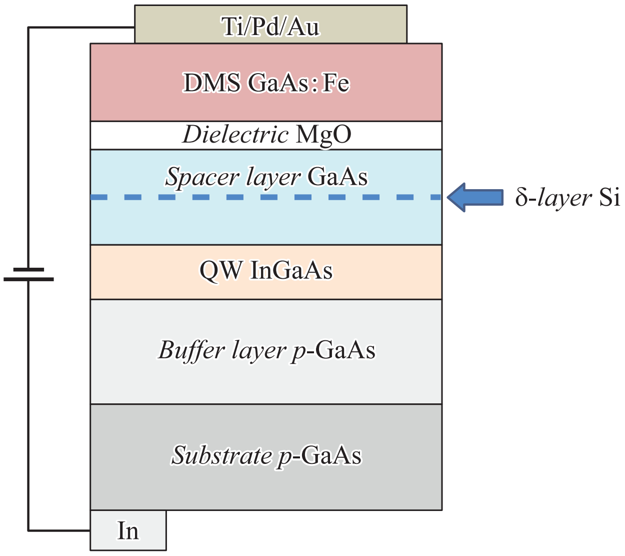

Figure 1. Diagram of the sample under study.

scattering times of the corresponding targets [8]). In the structures under study the concentration of Fe was 20 at.%.

It should be noted that process parameters of growing the layers of DMS GaAs:Fe studied in this work are similar to process parameters of the layers grown in [8]. Finally, ohmic contacts were formed to the structure and mesa-structure with a diameter of 500 μm were created by means of photolithography and chemical etching. Diagram of the grown sample is shown in Fig. 1.

To study the electroluminescence and I-V-curves, a forward bias (a negative potential applied to the top contact with respect to the substrate) was applied to the sample under study, and the radiation was recorded from the side of substrate. When the structure is introduced into a magnetic field normal to the surface, the radiation becomes partially circularly polarized. To study the dependence of the circular polarization on the magnetic field, the standard scheme of [3] was used with the degree of EL circular polarization calculated by the following formula

$$P_{\mathrm{EL}} = \frac{I_1 - I_2}{I_1 + I_2} \cdot 100\%, \qquad (1)$$

where P_{EL} is the degree of circular polarization of the EL, I_1 and I_2 are relative EL intensities measured for the light with left and right circular polarization, respectively. Measurements of I-V curves and the degree of circular polarization were carried out in Janis CCS-300S/202 cycle cryostat that allows measurements to be taken in the temperature range of 10–300 K.

Fig. 2 shows I-V curves of the sample under study at various temperatures. It can be seen that the I-V curves are of diode type. Due to the fact that GaAs:Fe is characterized by n-type conductivity [8], a $n-p$-junction is formed in the heterostructure shown in Fig. 1. As a result, an exponential growth of diode current is observed in the entire temperature range at a voltage polarity corresponding to the forward bias (negative potential on GaAs:Fe). In case of back bias the diode current is low and grows weakly with increase in the back voltage. The insert in Fig. 2 shows the EL spectrum of the sample under study measured with forward biased diode and a diode current of 10 mA. In the spectrum, one predominant peak is observed at ~ 1.31 eV that corresponds the main transition in the quantum well $\mathrm{In_{0.2}Ga_{0.8}As}$.

Fig. 3 shows that the magnitude of the degree of circular polarization P_{EL} for the sample under study with injector GaAs:Fe nonlinearly depends on the magnetic field. Note that at temperatures of 10, 50 and 75 K the $P_{\mathrm{EL}}(B)$ curve has a hysteresis loop (Fig. 3). The magnitude of the coercive field at a temperature of 10 K is 56 mT, at a temperature of 50 K it is 38 mT, and at a temperature of 75 K it is 5 mT. The hysteresis loop fully disappears with an increase in temperature above 75 K. The maximum degree of circular polarization due to magnetization intensity saturation was $\sim 0.4\%$. This value is weakly dependent on the measurement temperature in the range of 10–300 K. Probably, this type of dependence of the degree of circular polarization on magnetic field is related to magnetic properties of GaAs:Fe and is due to the injection of spin-polarized electrons from the ferromagnetic injector GaAs:Fe. We estimate the possible contribution of magnetic circular dichroism to the observed degree of circular polarization is not greater than 0.05%. The estimates were made on the basis of [8] where precisely this value of the magnetic circular dichroism was obtained for a quantum energy of ~ 1.31 eV corresponding to the LED radiation energy.

Also, measurements of the degree of circular polarization dependence on the magnetic field were curried out for the reference structure (an Al contact was deposited directly on the spacer layer GaAs instead of ferromagnetic injector GaAs:Fe). It can be seen in Fig. 3 that for the reference structure P_{EL} is a linear function of magnetic field (clear squares) and maximum degree of circular polarization is

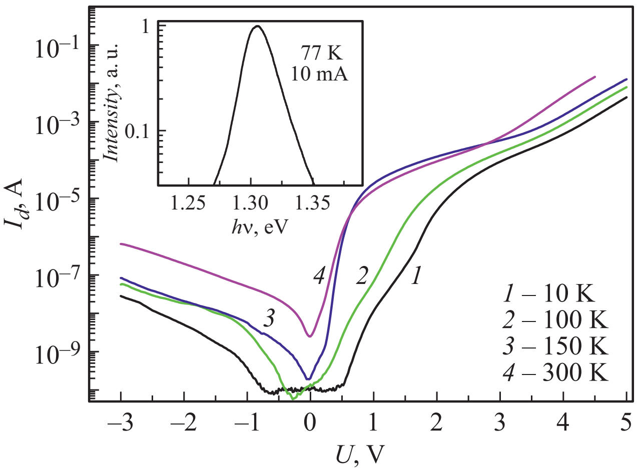

Figure 2. I-V curves of the sample under study at various temperatures. The insert illustrates spectrum of the electroluminescence.

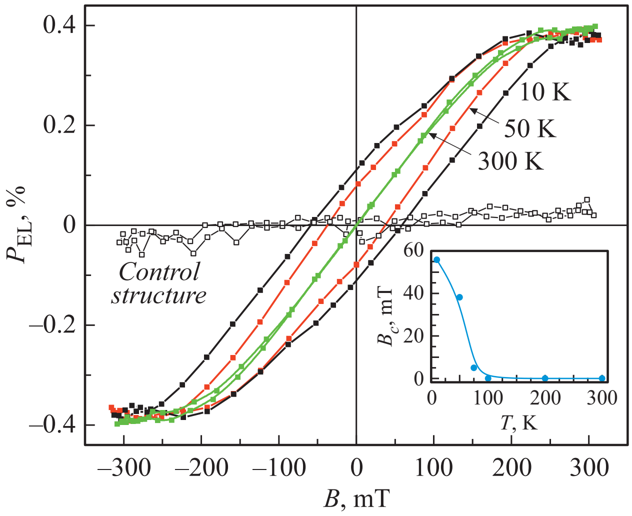

Figure 3. Magnetic field dependencies of P_{EL} for the sample under study at various temperatures, as well as for the reference structure (without the injector of GaAs:Fe) at a temperature of 10 K. The insert in the figure shows the coercive field as a function of temperature.

not more than 0.04%. With an increase in temperature the EL intensity for the sample under study monotonically decreases, while the degree of circular polarization does not depend on temperature. In addition, throughout the entire temperature range the attainment of saturation of the polarization dependence on the magnetic field was observed at the same values of magnetic field, i.e. about ±200 mT. Based on the obtained results, we assume that Curie temperature for the ferromagnetic injector GaAs:Fe exceeds 300 K. This conclusion is in good agreement with previous results obtained in [8] for GaAs:Fe with similar parameters. We associate the absence of hysteresis loop in the $P_{EL}(B)$ curve at temperatures above 75 K with the magnetic anisotropy of the formed films. For GaAs:Fe layers grown on i-GaAs substrates a perpendicular magnetic anisotropy was detected, which is related to the presence of Fe-enriched columnar regions in layers [8]. Polycrystalline structure of the DMS layer was observed in the LED with injector InSb:Fe/MgO [10]. In this study a GaAs:Fe layer was also deposited on the MgO layer, which expected to result in formation of polycrystalline structure of the GaAs:Fe layer (similar to [10]). As a consequence, probably no vertical Fe-enriched columns are formed, and the magnetic anisotropy of the DMS layer is determined by the anisotropy of the shape; therefore, the axis of the easy magnetization is oriented mainly in the plane of the layer.

Funding

This study was financially supported by the Russian Science Foundation (№ 18-79-10088).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] S.H. Liang, T.T. Zhang, P. Barate, J. Frougier, M. Vidal, P. Renucci, B. Xu, H. Jaffres, J.-M. George, X. Devaux, M. Hehn, X. Marie, S. Mangin, H.X. Yang, A. Hallal, M. Chshiev, T. Amand, H.F. Liu, D.P. Liu, X.F. Han, Z.G. Wang, Y. Lu, Phys. Rev. B, **90** (8), 085310 (2014). DOI: 10.1103/PhysRevB.90.085310

[2] R. Wang, X. Jiang, R.M. Shelby, R.M. Macfarlane, S.S.P. Parkin, S.R. Bank, J.S. Harris, Appl. Phys. Lett., **86** (5), 052901 (2005). DOI: 10.1063/1.1787896

[3] M. Holub, P. Bhattacharya, J. Phys. D: Appl. Phys., **40** (11), R179 (2007). DOI: 10.1088/0022-3727/40/11/R01

[4] N. Gerhardt, S. Hövel, C. Brenner, M. Hofmann, J. Appl. Phys., **99** (7), 073907 (2006). DOI: 10.1063/1.2186376

[5] D.K. Young, J.A. Gupta, E. Johnston-Halperin, R. Epstein, Y. Kato, D.D. Awschalom, Semicond. Sci. Technol., **17** (4), 275 (2002). DOI: 10.1088/0268-1242/17/4/301

[6] L. Chen, X. Yang, F. Yang, J. Zhao, J. Misuraca, P. Xiong, S.V. Molnár, Nano Lett., **11** (7), 2584 (2011). DOI: 10.1021/nl201187m

[7] N.T. Tu, P.N. Hai, L.D. Anh, M. Tanaka, Appl. Phys. Express, **11** (6), 063005 (2018). DOI: 10.7567/APEX.11.063005

[8] A.V. Kudrin, V.P. Lesnikov, Yu.A. Danilov, M.V. Dorokhin, O.V. Vikhrova, P.B. Demina, D.A. Pavlov, Yu.V. Usov, V.E. Milin, Yu.M. Kuznetsov, R.N. Kriukov, A.A. Konakov, N.Yu. Tabachkova, Semicond. Sci. Technol., **35** (12), 125032 (2020). DOI: 10.1088/1361-6641/abbd5c

[9] M.V. Ved, M.V. Dorokhin, V.P. Lesnikov, A.V. Zdoroveyshchev, Yu.A. Danilov, P.B. Demina, A.V. Kudrin, J. Phys.: Conf. Ser., **1410**, 012053 (2019). DOI: 10.1088/1742-6596/1410/1/012053

[10] M.V. Ved, M.V. Dorokhin, V.P. Lesnikov, A.V. Kudrin, P.B. Demina, A.V. Zdoroveyshchev, D.A. Pavlov, Yu.V. Usov, V.E. Milin, Yu.A. Danilov, Tech. Phys. Lett., **46** (7), 691 (2020). DOI: 10.1134/S1063785020070299.