RESEARCH ARTICLE | JUNE 22 2021

Quasi-one-dimensional chains of magnetic tunnel junctions as a source of THz radiation

V. G. Krishtop ✉; L. A. Fomin; A. V. Chernykh; E. A. Vilkov; S. S. Zhukov; E. S. Zhukova

AIP Conf. Proc. 2359, 020017 (2021)
https://doi.org/10.1063/5.0055018

Quasi-One-Dimensional Chains of Magnetic Tunnel Junctions as a Source of THz Radiation

V.G. Krishtop[1, a)], L.A. Fomin[1], A.V. Chernykh[1], E.A. Vilkov[2], S.S. Zhukov[3], E.S. Zhukova[3]

[1] *Institute of Microelectronics Technology and High Purity Materials RAS, Ac. Ossipyan str, 6, Chernogolovka, 142432, Russia*
[2]*Kotelnikov Institute of Radioengineering and Electronics RAS, Mokhovaya 11-7, Moscow, 125009, Russia*

[3]*Moscow Institute of Physics and Technology (National Research University), Institutskiy per. 9, Dolgoprudny, 141701, Russia*

[a)]Corresponding author: krishtop@iptm.ru

Abstract. The mechanism of formation of spin nonequilibrium with inverse population in spin subbands in quasi-one-dimensional chains of magnetic metal tunnel junctions is considered. The ability of induced spin-injected radiation is discussed. A model of a one-dimensional chain of ferromagnetic metal grains separated by a tunneling dielectric under the influence of electric current is considered. The radiation spectra of grainy metamaterials were measured in the terahertz range depending on the average current density in the Q1D-labyrinth structures.

A promising mechanism for organizing THz radiation in point contacts of magnetic materials (ferromagnetic and antiferromagnetic metals, FM and AFM) is the formation of an inverse population in spin subbands by injecting spin-nonequilibrium electrons by a strong electric current from a material with one magnetic property into a material with other magnetic properties.

The mechanism of formation of spin nonequilibrium with inverse population in spin subbands with the possibility of induced spin-flip radiation in magnetic metal contacts was discussed in detail in [1-3] for FM–FM [2] and FM–AFM structures [3]. The theory of spin-flip radiation was presented in [4-6]. Experimental confirmations of the spin-flip THz radiation in point current contacts of a normal metal-ferromagnet with a high current density were obtained in [7–13].

An electron passing through the contact successively passes through three regions (Fig. 1.). First, the contact area, magnetized perpendicular to the film. Secondly, the region of nonequilibrium electrons, in which the nonequilibrium population of spin subbands, and where the relaxation occurs (including the spin relaxation, including the spin relaxation with the emission of a terahertz photon). And finally, the electron come into the equilibrium region with parallel magnetization.

The natural desire to increase the efficiency of the spin-injection terahertz radiation source has led to the fabrication of magnetic injection contact arrays by lithographic techniques [14-16]. It also seems appropriate to organize a tunnel barrier between materials for a higher disequilibrium of spin subband population. Quasi-one-dimensional chains of tunneling magnetic nanocontacts combine the advantages of various approaches, and do not require the high-precision and expensive nanolithography.

Pulsed laser deposition (PLD) is a powerful technique for the controlled growth of granular films with partial epitaxy. Using pulsed laser deposition of metals on a heated substrate with "in situ" control of film parameters, it is possible to control grain size, manage to achieve partial epitaxy and achieve right grain sizes and density of surface filling with grains. The controlled growth of the films makes it possible to well predict the percolation threshold, and also to control it in a small range.

Proceedings of International Congress on Graphene, 2D Materials and Applications (2D Materials 2019)
AIP Conf. Proc. 2359, 020017-1–020017-4; https://doi.org/10.1063/5.0055018
Published by AIP Publishing. 978-0-7354-4103-3/$30.00

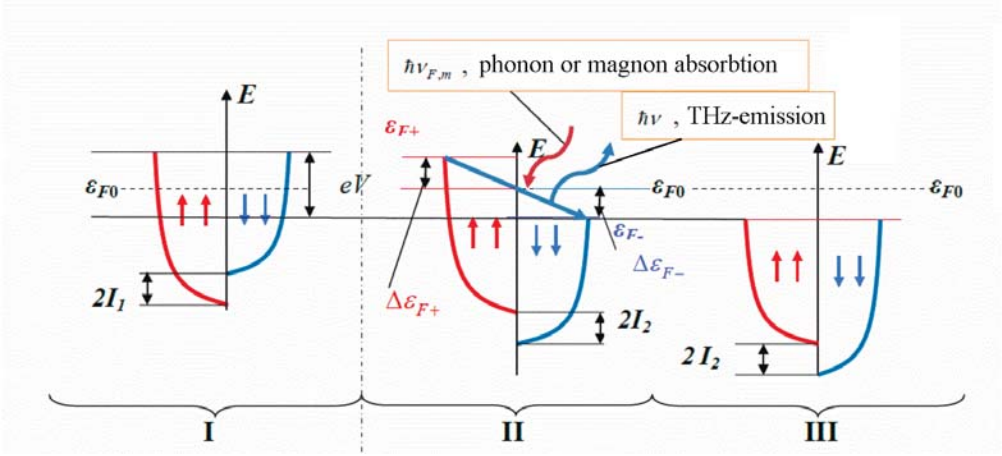

FIGURE 1. Scheme of energy electron bands and quasi-Fermi levels: I — in nanocontact; II — the region of nonequilibrium electrons in the film (the energy subband for minor electrons is populated by injection); III — for equilibrium electrons in the film. An indirect interband transition of an electron with spin flip in the energy interval between two nonequilibrium Fermi quasilevels with emission/absorption of a third particle is possible. V is the potential difference between the upper electrode and the film; I_1 and I_2 are the exchange energies in nanocontact and film; E_{F0} is the equilibrium value of the Fermi level with the voltage off.

Moreover, in the process of film growth immediately before the percolation threshold, the merging grains are organized into long percolated one-dimensional chains, which nevertheless do not yet provide the ohmic current in structure. These chains are called "labyrinth structures".

To organize the pre-labyrinth structure with the tunnel junctions, it remains to take another step back from the percolation threshold and stop the film growth a little earlier than the grains begin to merge into the labyrinths. In this case, we obtain pre-labyrinth chains composed of individual grains separated by tunnel junctions in the thinnest places of their touch. The electric current in the pre-labyrinth film will propagate mainly along these chains, overcoming a series of tunnel junctions along the way.

Examples of the morphology of pre-percolated films are shown in Fig. 2. The surface morphology of this films was studied by atomic force microscopy (AFM).

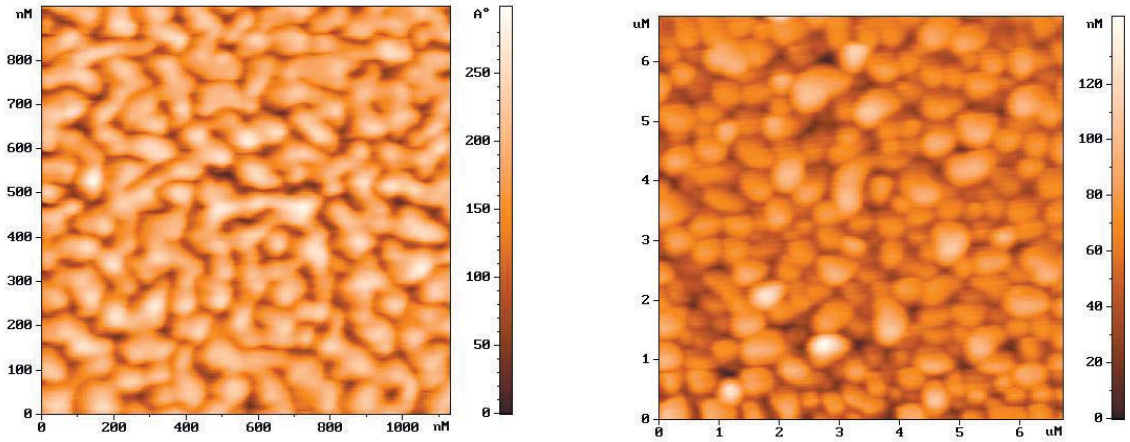

FIGURE 2. Granular films of magnetic materials. (a) — Fe/FeMn film with labyrinth structures near the percolation threshold. (b) — Fe/FeMn film with pre-labyrinth quasi-one-dimensional chains of tunnel junctions a bit further from the percolation threshold.

In this report, we consider the mechanism of formation of spin nonequilibrium with inverse population in spin subbands with the ability of induced spin-injected radiation in quasi-one-dimensional chains of magnetic metal tunnel junctions. A model of a one-dimensional chain of ferromagnetic metal grains separated by a tunneling diel ectric under the influence of electric current is considered. The radiation spectra of grainy metamaterials were measured in the terahertz range depending on the average current density in the Q1D-labyrinth structures.

The polarization in the grains was estimated based on the simplest one-dimensional model (Fig. 3). The spin balance equations were written in terms of the Landauer expressions for partial currents, under the grains electroneutrality condition and the electric current conservation condition. We estimated the magnitude of the spin polarization [17, 18] and estimated the current required for the inverse population of spin subbands. It should be noted that the inverse level population is not necessary for spin-flip emission.

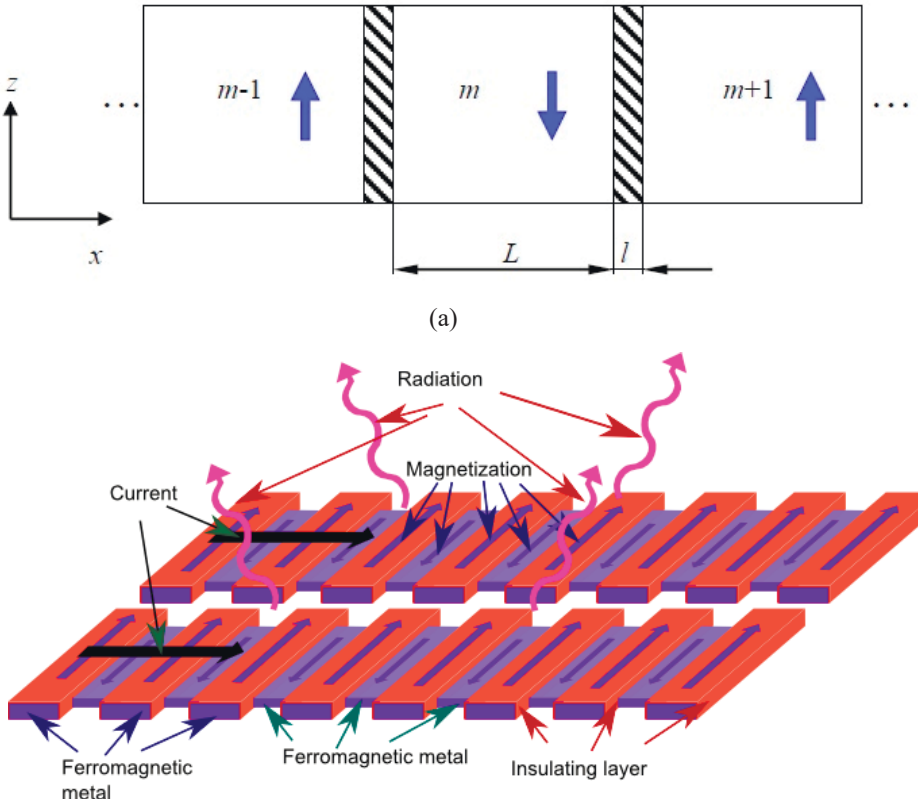

FIGURE 3. Model of a one-dimensional tunnel junction chain (a). The planar structure of one-dimensional chains with alternating grains of a ferromagnet and an antiferromagnet (b).

REFERENCES

1. Gulyaev Yu.V., Vilkov E.A., Zil'Berman P.E., Mikhailov G.M., Chigarev S.G., J. Commun. Technol. Electron. 58, № 12, 1137-1141 (2013). DOI: 10.1134/S1064226913110077
2. Gulyaev Yu.V., Vilkov E.A., ZilBerman P.E., Mikhailov G.M., Chigarev S.G., Phys.-Dokl. 58, № 8, 347-348 (2013). DOI: /10.1134/S1028335813080016

3. Yu. V. Gulyaev, E. A. Vilkov, P. E. Zil'berman, G. M. Mikhailov, S. G. Chigarev, E. M. Epshtein, JETP Letters **98**, 96–100 (2013). DOI: 10.1134/S0021364013150095.
4. Gulyaev Y.V., Zilberman P.E., Epshtein E.M., J. Exp. Theor. Phys. **114**(2). 296-304 (2012). DOI: 10.1134/S1063776112010013.
5. Gulyaev Y.V., Zilberman P.E., Epshtein E.M., J. Commun. Technol. Electron. **57**(5), 506-511 (2012). DOI: 10.1134/S106422691205004X.
6. Gulyaev Yu.V., Zilberman P.E., Kotov V.D., Chigarev S.G., Epshtein E.M., Mikhailov G.M., J. Commun. Technol. Electron. **57**(8). 813-817 (2012). DOI: 10.1134/S1064226912080165.
7. Gulyaev Yu.V., Zil'berman P.E., Krikunov A.I., Panas A.I., Éphshteĭn E.M., JETP letters **85**(3), 160-164 (2007). DOI: 10.1134/S002136400703006X.
8. Gulyaev Y.V., Zilberman P.E., Chigarev S.G., Epshtein E.M., Malikov I.V., Mikhailov G.M., J. Commun. Technol. Electron. **57**(3), 329-334 (2012). DOI: 10.1134/S1064226912030096.
9. Chigarev S.G., Krikunov A.I., Zilberman P.E., Panas A.I., Epshtein E.M., J. Commun. Technol. Electron. **54**(6), 708-712 (2009). DOI: 10.1134/S1064226909060138.
10. Gulyaev Y.V., Zilberman P.E., Panas A.I., Chigarev S.G., Epshtein E.M., J. Commun. Technol. Electron. **55**(6), 715-719 (2010).
11. Gulyaev Y.V., Zilberman P.E., Chigarev S.G., Epshtein E.M., J. Commun. Technol. Electron. **55**(10), 1211-1215 (2010).
12. Gulyaev Y.V., Zilberman P.E., Panas A.I., Chigarev S.G., Epshtein E.M., Malikov I.V., Mikhailov G.M., JETP Letters **93**(5), 259-262 (2011). DOI: 10.1134/S0021364011050055.
13. S.G. Chigarev, E.M. Epshtein, Y.V. Gulyaev, I.V. Malikov, G.M. Mikhailov, V.G. Shofman, P.E. Zilberman, Solid State Phenomena **190**, 153-156 (2012). DOI: 10.4028/www.scientific.net/SSP.190.153.
14. R.I. Shekhter, A.M. Kadigrobov, M. Jonson, E.I. Smotrova, A.I. Nosich, V. Korenivski, Optics Letters, **36**(12), 2381-2383 (2011). DOI: 10.1364/OL.36.002381.
15. V. Korenivski, A. Iovan, A. Kadigrobov, R.I. Shekhter, Europhysics Letters (EPL) **104**(2), 27011 (2013). DOI: 10.1209/0295-5075/104/27011.
16. A. Iovan, M. Fischer, R. Lo Conte, V. Korenivski, Beilstein J. Nanotechnol. **3**, 884–892 (2012). DOI: 10.3762/bjnano.3.98.
17. L.A. Fomin, E.A. Vilkov, V.G. Krishtop, E.S. Zhukova, A.V. Chernykh, *Tunnel structure of magnetic grainy metamaterial as a source of THz radiation based on spin-flip transitions*, Proceedings of the XVII All-Russian School-Seminar "Physics and Application of Microwaves" edited by A.N. Kalish, Section 10, Spintronics and Magnonics (Mozhaisk, 2019), pp.14-17.
18. V.G. Krishtop, E.C. Zhukova, L.A. Fomin, A.V. Chernykh, G.M. Mikhailov, *Radiation spectra of nanostructured films of magnetic metals*, Proceedings of the XXII International Symposium "Nanophysics and Nanoelectronics" **1**, (Nizhny Novgorod, 2018), pp. 208-209.