Pis'ma v ZhETF, vol. 76, iss. 7, pp. 547 – 549 © 2002 October 10

Observation of a light-induced nonohmic current in a toroidal-moment-possessive nanostructure

S. A. Emelyanov[1)], B. Ya. Meltser[+], S. V. Ivanov[+]

Division of Solid State Electronics, A. F. Ioffe Institute, 194021 St.Petersburg, Russia

[+]*Center of Nanoheterostructures, A. F. Ioffe Institute, 194021 St.Petersburg, Russia*

Submitted 5 September 2002

We report on the first observation of light-induced nonohmic current in a semiconductor nanostructure. The effect is revealed in unbiased asymmetric InAs quantum well under the excitation by far-infrared laser radiation in presence of a tilted magnetic field. It is interpreted in terms of nonzero toroidal moment of the two-dimensional electron gas.

PACS: 73.20.Dx, 73.50.–h

Even in the framework of classical electrodynamics, it can be shown that for complete characterization of the system possessive of an arbitrary distribution of currents and charges, three independent families of electromagnetic multipoles should be taken into account: electric, magnetic and toroidal moments [1]. The first two families are well known for a very long time while the third one was introduced not so long ago, in 1957, by Ya. B. Zel'dovich [2] to explain the effect of parity violation under weak interactions in nuclear systems (for the concept of toroidal moment, see, e.g., [3, 4] and refs. therein). Since 1978 a number of theoretical works have been made related to the various aspects of so-called toroidal state of condensed matters, which is characterized by nonzero toroidal moment density (see, e.g., [5]). The most nontrivial effects predicted for toroidal-moment-possessive systems are related to their magnetic properties. One of such effects is the so-called superdiamagnetism which implies a system in nonsuperconducting phase possessive of a gigantic diamagnetic susceptibility closed to theoretical limit [6].

The idea that in-plane magnetic field gives rise to toroidal dipole moment in asymmetric nanostructures was first proposed in [7]. It was shown that nonzero toroidal moment is always accompanied by an asymmetry of the energy spectrum of the system ($E(k) \neq E(-k)$) and k-dependent excitation of such system may result in a drift electric current in it as well as in an electric polarization. In the limit of low magnetic fields, these effects can be described by the following phenomenological relations:

$$J = \beta T; \tag{1}$$

$$P \sim [BT] \equiv [B[BI]], \tag{2}$$

where T is a time-odd polar vector which is just the toroidal dipole moment, β is a dissipation coefficient, I is a polar vector perpendicular to the well plane. Thus, k-dependent excitation of an asymmetric nanostructure in presence of the magnetic field tilted in XZ plane (Z is the growth axis) may result in a drift current along Y-axis proportional to B_x as well as in an electric polarization in XZ plane which is proportional to $B_x \cdot B_z$. The former effect has been observed in asymmetrical quantum structures either under photoexcitation [8 – 10] or under the excitation by an external electric field [11]. However, no signatures of the latter effect have been observed up to now.

In this Letter we report on the first observation of a light-induced nonohmic current related to nonzero toroidal moment of a two-dimensional (2D) electron gas. The experiments were performed on (001)-MBE grown InAs/GaSb single quantum well structures supplied by thin AlSb barriers to avoid hybridization-related effects [12]. Typical structure consists of 15 nm InAs channel sandwiched between two 0.3 nm wide AlSb barriers and capped by a 20 nm GaSb layer. Low-temperature electron sheet density and mobility are $1.7 \cdot 10^{12}\,\mathrm{cm}^{-2}$ and $1.5 \cdot 10^{5}\,\mathrm{cm}^2/\mathrm{V \cdot s}$, respectively. Each device is supplied by a pair of strip-like ohmic contacts. High-power pulsed NH_3 laser optically pumped by CO_2 laser was used as a source of far-infrared radiation. The laser wavelength was 90.6 μm, pulse duration was about 30 ns, peak laser radiation intensity was of order 100 W/cm^2. Magnetic field was provided by superconducting solenoid. The experiments were performed at 4.2 K under normal incidence of the light on the sample surface. Light-induced in-plane currents in unbiased devices were detected through the voltage drop on 50 Ohm

1)e-mail: sergey.emelyanov@mail.rssi.ru

load resistor in a short-circuit regime by high-speed storage oscilloscope. The in-plane current was measured in two directions: either across or along the in-plane component of the magnetic field. The former experimental geometry is shown in the inset of Fig.1. The latter geometry one can obtain by clockwise rotation of the sample by 90° about Z-axis.

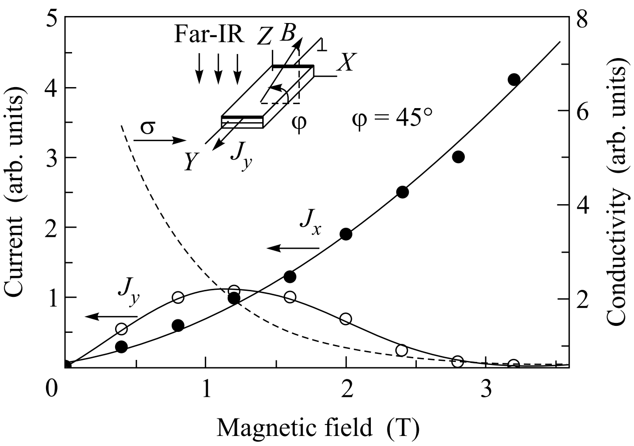

Fig.1. Light-induced currents as a function of the magnetic field B at $\varphi = 45°$. Solid circles – J_x, open circles – J_y. Solid curves are an interpolation of the experimental data. Dotted curve is the device ohmic conductivity as a function of B. The inset shows the geometry of the measurements of J_y. That of J_x can be obtained by clockwise rotation of the sample by 90° about Z-axis

Pronounced current pulses have been observed in both X and Y directions. These pulses copy the shape of the initial laser pulses indicating that the process responsible for their arising is of a steady-state character with response time of less than 10^{-7} s. The currents are found to be independent of both light direction and polarization as well as of the orientation of crystallographic axis in the well plane. This means the currents are caused not by an asymmetry carried by light but by the inner system asymmetry that is built-in electric field across the well [13]. The current along Y-axis (J_y) is odd on the external magnetic field B while the current along X-axis (J_x) is even on B. Switching of the angle between the magnetic field and the well plane from φ to $-\varphi$ reverses the sign of J_x while the sign of J_y remains. The dependencies of both J_x and J_y versus B at $\varphi = 45°$ are shown in Fig.1 as well as the behaviour of device ohmic conductivity σ. It is seen that, at low magnetic fields, J_y is proportional to B but then it goes to zero with increasing of B because of the drastic drop of σ. Surprisingly, J_x is clearly insensate to σ and it increases roughly as B^2. To demonstrate this point unambiguously, the angle dependencies of both J_x and J_y at $B = 2T$ are plotted in Fig.2 together with the angle

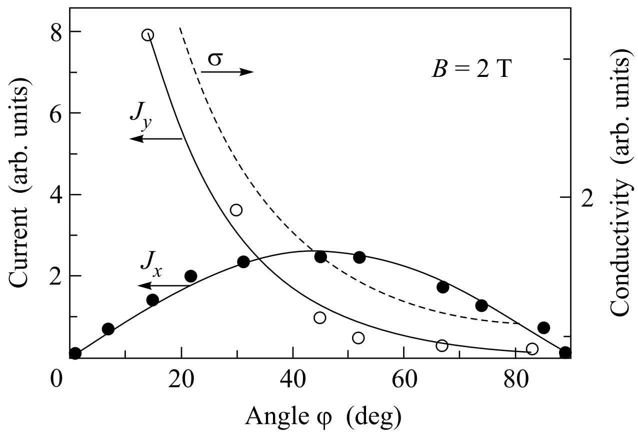

Fig.2. Light-induced currents as a function of the angle φ at $B = 2$ T. Solid circles – J_x, open circles – J_y. Solid curves are an interpolation of the experimental data. Dotted curve is the device ohmic conductivity as a function of φ

dependence of σ. Once again, J_y reduces with increasing of B whereas J_x is clearly insensate to σ and its behaviour looks like an ideal sinusoid with double angle φ as an argument.

It is easy to see that our experimental results are in a good agreement with phenomenological relations (1) and (2). To clarify microscopic picture of the effect, let us consider the details of the photoexcitation process. It is well known that 15-nm-thick InAs quantum well contains highly degenerated two-dimensional electron gas. The minimum electron sheet density for occupation of the 2nd quantum-size level is known to be about $2.2 \cdot 10^{-12}$ cm^{-2} [14]. Since in our structures this value is about $1.6 \cdot 10^{-12}$ cm^{-2}, the only 1st quantum-size level is occupied at low temperatures so that the effects related to presence of the 2nd level can be ignored. Further, since both J_y and J_x are independent of light polarization (left- or right-hand circular), the spin-related effects (see, e.g., [15, 16]) can also be ignored. Taking into account that (i) the energy of light quantum in our experiments is as low as 13.7 meV and (ii) B_z is too low to access cyclotron resonance conditions, one would expect that phonon-assisted optical transitions (Drude-like process) is predominant mechanism of the light absorption. This means that the photoexcitation process is a k-dependent one. Thus, the current J_y can be identified as a conventional drift photogalvanic current which is related to an imbalance between k-dependent optical transitions within an asymmetrical energy spectrum.

As for the current J_x, its mechanism is not so evident. First, the nonohmic nature of J_x indicates that the electrons should be localized along X-axis. Moreover, polarization effect, predicted in Ref. [7], also implies Landau-quantization-related localization of the electrons along X-axis as well as their quasi-free motion along Y-axis. Thus, as a result of the Lorentz force effect, each of them is supposed to be possessive of an electric dipole moment so that the total electric dipole moment of the unexcited electron gas should be equal to zero. On the other hand, the Landau quantization at relatively low B is supported also experimentally by observation of well resolved Shubnikov-de Haas oscillations in InAs quantum wells when quantizing magnetic field is as low as 1 T or even less [17,18]. Therefore, despite of the in-plane electron motion is not fully suppressed by quantizing component of the magnetic field (otherwise, J_y should be equal to zero), Landau-localization-related effects may be of importance under the experimental conditions. In this sense, the current J_x may be interpreted as being due to the nonzero net electric dipole moment of the 2D electron gas resulted from the k-dependent photoexcitation.

However, it should be noted that, in the framework of the concept of toroidal moment, one can propose an alternative microscopic mechanism of the current J_x. Indeed, as it has also been predicted in Ref. [7], Landau quantization in a toroidal-moment-possessive nanostructure may be accompanied by a spatial separation of the electrons along X-axis depending on their wave vector along Y-axis. In this case, each phonon-assisted optical transition in k-space should be accompanied by an appropriate hopping-like transition in real space along X-axis as an integral part of the same absorption act. Therefore, taking into account the energy spectrum asymmetry, the k-dependent photoexcitation may result in a nonzero net hopping in real space along X-axis. Such a process could also be the reason for the nonohmic current. Thus, identification of microscopic mechanism of the light-induced nonohmic current under the experimental conditions clearly requires further experiments which will be done in the near future.

The authors would like to thank A. P. Dmitriev for useful discussions. Invaluable contribution to the experimental design by S. D. Ganichev and Ya.V.Terent'ev is acknowledged. The work is supported in part by RFBR (Grants # 00-02-17045; 01-02-17933) and by RF Program "Nanostructures", at the final stage also by INTAS (Grant # 99-01146) and by SNSF (Grant # 7SUPJ062181).

1. V. M. Dubovik and A. A. Cheshkov, Sov. J. Part. Nucl. **5**, 318 (1975).
2. B. Ya. Zel'dovich, Sov. Phys. JETP **6**, 1184 (1958).
3. V. M. Dubovik and L. A. Tosunyan, Sov. J. Part. Nucl. **14**, 504 (1983).
4. V. M. Dubovik, M. A. Martsenyuk, and Bijan Saha, Phys. Rev. **E61**, 7087 (2000).
5. A. A. Gorbatsevich and Yu. V. Kopaev, Ferroelectrics **161**, 321 (1994).
6. V. L. Ginzburg, A. A. Gorbatsevich, Yu. V. Kopaev, and B. A. Volkov, Sol. St. Comm. **50**, 339 (1984).
7. A. A. Gorbatsevich, V. V. Kapaev, and Yu. V. Kopaev, JETP Lett. **57**, 580 (1993).
8. A. P. Dmitriev, S. A. Emel'yanov, S. V. Ivanov et al., JETP Lett. **54**, 279 (1991).
9. Yu. A. Aleshchenko, I. D. Voronova, S. P. Grishechkina et al., JETP Lett. **58**, 384 (1993).
10. O. E. Omel'yanovskii, V. I. Tsebro, V. I. Kadushkin et al., JETP Lett. **63**, 209 (1996).
11. A. A. Gorbatsevich, V. V. Kapaev, Yu. V. Kopaev et al., JETP **93**, 833 (2001).
12. S. de-Leon, L. D. Shvartsman, and B. Laikhtman, Phys. Rev. **B60**, 1861 (1999).
13. It is not necessary to confirm the presence of built-in electric field in our structures since the existence of a light-induced current independent of both light direction and polarization as well as of the orientation of crystallographic axis, is, in itself, such a confirmation. Most likely, this field is related to an uncontrolled asymmetric ionization of interface donor states (see e.g., H. Kroemer, C. Nguyen, and B. Brar, J. Vac. Sci. Technol. **B10**, 1769 (1992)).
14. A. C. H. Rowe, R. S. Ferguson, and R. A. Stradling, in *Proc. of the 25th Int. Conf. on the Physics of Semiconductors*, Eds. N. Miura and T. Ando, Springer, 2001, Part 1, p. 765.
15. S. D. Ganichev, E. L. Ivchenko, S. N. Danilov et al., Phys. Rev. Lett. **86**, 4358 (2001).
16. S. D. Ganichev, V. V. Bel'kov, E. L. Ivchenko et al., in *Proc. of the 9th Int. Symp. "Nanostructures: Physics and Technology"*, St.Petersburg, Russia, 19-23 June 2001, p. 252.
17. J. Luo, H. Munekata, F. F. Fang, and P. J. Stiles, Phys. Rev. **B38**, 10142 (1988).
18. S. Brosig, K. Ensslin, B. Brar et al., Physica **B256-258**, 239 (1998).