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Plasmonics
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A scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS), entitled 'Plasmonics', was held in the Conference Hall of the Lebedev Physical Institute, RAS on 21 February 2012.

The following reports were put on the session agenda posted on the website www.gpad.ac.ru of the RAS Physical Sciences Division:

(1) **Kukushkin I V, Murav'ev V M** (Institute of Solid State Physics, RAS, Chernogolovka, Moscow region) "Terahertz plasmonics";

(2) **Lozovik Yu E** (Institute of Spectroscopy, RAS, Troitsk, Moscow region) "Plasmonics and magnetoplasmonics based on graphene and a topological insulator";

(3) **Protsenko I E** (P N Lebedev Physical Institute, RAS, Moscow) "Dipole nanolaser";

(4) **Vinogradov A P, Andrianov E S, Pukhov A A, Dorofeenko A V** (Institute for Theoretical and Applied Electrodynamics, RAS, Moscow), **Lisyansky A A** (Queens College of the City University of New York, USA) "Quantum plasmonics of metamaterials: loss compensation using spasers";

(5) **Klimov V V** (Lebedev Physical Institute, RAS, Moscow) "Quantum theory of radiation of optically active molecules in the vicinity of chiral nano-meta-particles".

The papers written on the basis of oral reports 2–5 are published below.

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Plasmonics and magnetoplasmonics based on graphene and a topological insulator

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Plasmonics is one of the most rapidly developing interdisciplinary branches of physics. From the fundamental point of view, plasma oscillations in solids comprise collective oscillations of electron gas density controlled by Coulomb electron interaction; in the simplest case, the oscillation dispersion law is defined by the electron concentration in the conduction band, the permittivity of the medium (of the crystal without the inclusion of conduction electrons), and their effective mass. In the general case, for instance, for interband plasmons, the plasmon dispersion law depends on the electron band structure. The damping of plasma oscillations is determined both by single-particle mechanisms of carrier scattering by impurities, etc. and by Landau damping. In microscopic terms, the latter corresponds to the decay of a plasma oscillation quantum — a plasmon — into two single-particle excitations: an electron and a hole. To state it in macroscopic terms, as shown by Ginzburg, this decay constitutes an inverse Vavilov–Cherenkov effect (electron acceleration by the field of a plasma wave). Plasmon excitation, for instance, with the help of characteristic electron losses was employed for the description of solids (see Refs [1–3] and references cited therein).

Plasmonics emerged from the study of plasmons in low-dimensional systems and structures and from the development of their applications. The specific character of (surface and local) plasmons in these systems consists in the fact that the frequency and damping of plasmons in them is defined by the geometry of the structure and the permittivity of the environment, because the lines of force of the Coulomb fields of the interacting electrons also pass through the ambient medium [4–7]. The last circumstance may be used for creating supersensitive plasmon sensors (see Ref. [8] and references cited therein). Plasmon excitation is widely used in surface spectroscopy [9, 10], and local plasmon excitation is employed for a giant enhancement of Raman light scattering [11] and of different nonlinear optical processes (see, for instance, Ref. [12] and references cited therein). It would be instructive to produce a complete set of control elements for two-dimensional, surface plasmon optics (plasmon mirrors, lenses, etc.). The feasibility of realizing time-resolved surface plasmon optics has also been discussed, and the first successful steps in this direction have been reported [13, 14]. The excitation of local plasmons on the tip of a scanning probe microscope by an incident electromagnetic wave may be employed for producing under the tip a subwavelength domain with a strongly enhanced field; this, in turn, was used for local spectroscopy and nanolithography with an ultrahigh spatial resolution which far exceeded the Rayleigh limit (see Refs [15–17] and references cited therein).

Another possible application of plasmons and plasmon polaritons is ultrafast information transfer (for instance, between the elements of a chip), faster than with electron current pulses. Lastly, an interesting possibility consists in the

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development of quantum plasmonics for quantum informatics, etc.

All these promising applications are significantly limited by the damping of plasmons — by their finite mean free path. This impediment can be overcome with the aid of active plasmonics by using spasers — plasmon analogs of lasers [18–20]. In particular, it will be possible by using a spaser in the form of the tip of a scanning probe microscope and measuring the loss-induced dips in its generation spectrum to realize supersensitive spectroscopy with an ultrahigh spatial resolution [21], which represents, in a sense, a spaser analog of selective near-field laser spectroscopy [22]. This method may also be utilized for the supersensitive spaser spectroscopy of surfaces [23]. Spasers are also the concern of reports to this session of the Physical Sciences Division of the RAS [24, 25].

Another method of overcoming the specified difficulty involves the search for and use of radically new systems with a weak plasmon damping like doped graphene. Below, we briefly discuss the collective electronic and optical properties of graphene and topological insulators, which were analyzed in our work.

From the fundamental standpoint, the keen interest in graphene — a single isolated plane of graphite, which is stable even without a substrate (see reviews [26–35] and references cited therein) — and in recently discovered (three-dimensional) topological insulators (see reviews [36, 37] and references cited therein) is due to the fact that in these entirely different materials — graphene and topological insulator surfaces — there is a two-dimensional electron gas with a zero effective mass and a zero gap between the conduction and valence bands. This two-dimensional electron gas is described by the Dirac equation with a zero mass (as for neutrinos!), and therefore one may draw an analogy to ultrarelativistic physics of elementary particles and quark matter. This leads to a number of interesting effects comprising the absence of backward reflection from potential barriers at normal incidence (Klein tunneling), weak antilocalization, and the half-integer quantum Hall effect (observable even at room temperature!).

A difference from ultrarelativistic particle physics must also be emphasized: in the Dirac equation for graphene, in place of the speed of light a quantity 300 times lower appears, and this equation is valid only in the laboratory frame of reference (because in the derivation of the effective Dirac equation for graphene they proceed from the Galilean-invariant Schrödinger equation).

Certainly, it should be remembered that these are the so-called envelopes obeying the Dirac equation in an external field. These envelopes describe the slow modulation (due to slowly varying external fields) of Bloch functions which oscillate with a lattice period (used in this case is the adiabatic approximation which leads for ordinary crystals to the Schrödinger equation with an effective mass).

The linear dispersion law for graphene was first established [38, 39] proceeding from the Schrödinger equation which took into account the symmetry and the existence of two sublattices in graphene, within an approximation accounting for the closest neighbor interaction. But this linear spectrum (valid up to an energy on the order of 1 eV), i.e. the presence of Dirac-effective electrons, is associated, as may be shown, with the symmetry of graphene, and this property is protected from the presence of impurities and some other perturbations by symmetry with respect to time reversal. The role of spin in the Dirac equation is played by pseudospin which emerges due to the fact that the hexagonal lattice in graphene may be represented in the form of two equivalent triangular lattices displaced relative to each other. The presence of two more components in the Dirac equation for graphene is associated with the existence of two independent valleys in the Brillouin zone for graphene (since the existence of two sites in the graphene elementary cell results in two sites in the elementary cell of the reciprocal lattice).

The interest in graphene, of course, is spurred by the prospect of numerous applications related to its unique properties. Graphene is one atom thick, so that an extremely small size as a possible element of nanoelectronics or optoelectronics is reached in one dimension. It is valid to say that a new class of materials made its appearance owing to the discovery of graphene — two-dimensional membranes stable even without a substrate. Graphene is compatible with the traditional technology of the planar nanostructure production (unlike, for instance, nanotubes). It may posses a high electron mobility even at room temperature, and its thermal conductivity is significantly higher than that of copper. Furthermore, the intrinsic strength of graphene is 200 times greater than the strength of steel. Owing to these remarkable properties, graphene shows promise for making coatings of solar batteries and screens, new composite nanomaterials, ultracapacitors, and nanoelectronic elements.

An interesting property of graphene consists in the possibility of changing its transport characteristics upon adsorption of molecules, etc., which opens the prospect of making supersensitive nanosensors on its basis.

An important property of graphene is the possibility of easily controling the density of electrons or holes with the help of external control electrodes (or external chemical doping).

Such a property may be employed for transistors, though only for analog transistors, not digital ones. This is due to the absence of an energy gap in graphene, because there is no way of blocking the electric current in digital transistors. However, opening the gap with the aid of geometrical quantization — by using graphene tapes or bigraphene in a transverse electric field — will permit the employment of such systems in digital transistors as well. The application of concentration guiding with control electrodes in a bilayer graphene system was proposed for making a system of two separated layers of Dirac electrons and holes of equal concentrations. Possible in this system is the Bose–Einstein condensation (BEC) of dipole pairs or excitons from spatially separated electrons and holes in a magnetic field [40–42] (which exist in graphene only in a magnetic field owing to the absence of backward reflection of electrons) or their Bardeen–Cooper–Schrieffer (BCS) type pairing (see Refs [43–52]) due to Coulomb attraction (similar to the pairing in a three-dimensional excitonic insulator [53, 54]), which leads to the appearance of undamped electric currents in each of the layers in the system under consideration. The difference between a graphene bilayer and a bilayer of paired electrons and holes with a nonzero mass [55] consists in the absence of the ordinary BEC–BCS crossover (without a magnetic field) upon lowering the pairing particle concentration and the existence of an angular factor associated with the spinor nature of the Dirac wave function, the factor which suppresses backward scattering. The system considered here may be utilized as a dissipation-free information transfer line. A similar system of spatially separated Dirac electrons and holes and their pairing and superfluidity may be realized by independent doping with the help of independent control electrodes for the opposite surfaces of the superthin film of a topological insulator (see Ref. [56] and references cited therein). Heavy doping may give rise to intrinsic superconductivity in graphene (see Ref. [57] and references cited therein).

The specific character of the graphene's band structure results in interesting features of its dielectric response: to the existence of a singularity in the low-frequency range (like for a metal, though weaker), to highly unusual optical properties [58], and to a weak damping of quasiparticles in it. These properties show good promise of making photonic crystals on the base of graphene which has a photonic gap in the far-infrared spectral region hardly blurred by damping (unlike that in metals) [59].

The possibility of controling the electron concentration in graphene with the aid of control electrodes opens the door to graphene-based plasmonics [60–64]. In particular, it is possible to make plasmon waveguides and plasmon switches using the specially profiled coatings and control electrodes on graphene. Critically important additional virtues of graphene for plasmonics are a weak damping, a long mean free path of plasmons in it, and the capability of working in the terahertz frequency range. The weak damping opens the way for the development of a graphene-based quantum plasmonics or single-plasmonics.

It will be of interest to control plasmons in graphene and nanomaterials based on it with the help of an external magnetic field (see Ref. [62] and references cited therein). We analyzed the properties of polaritons in an optical microcavity with graphene embedded into it (Fig. 1) and their properties in the terahertz frequency range [63, 64]. We also considered the TE and TM modes in graphene which borders on two adjacent media with a low dielectric contrast

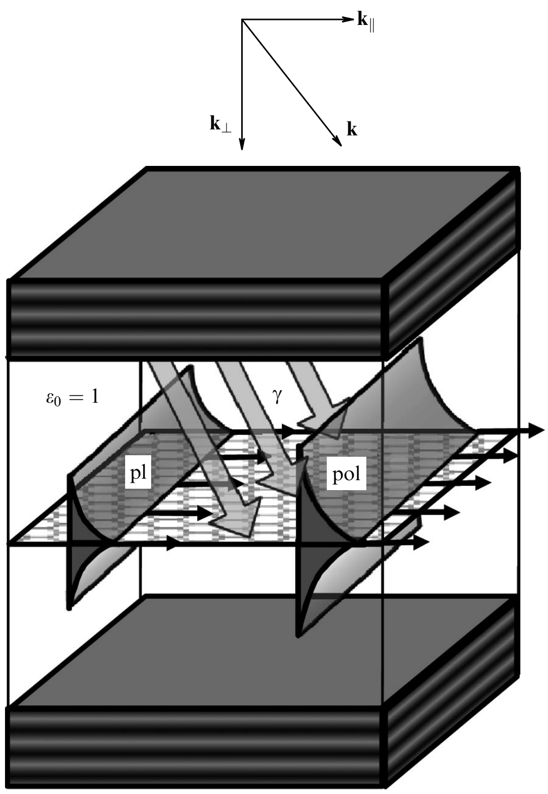

Figure 1. Polariton (pol) in an optical microcavity wherein graphene is embedded; pl is a plasmon, and γ is a photon.

between them. In the frequency range where the imaginary part of the permittivity is small, the properties of the system turned out to be critically dependent on the low dielectric contrast between the media. This leads to a leakage of surface waves, which permits making an ultrahigh-sensitivity sensor on the base of this system [65].

Also of interest is the possibility of controling collective excitations in graphene as well as polaritons in an optical microcavity, which graphene is embedded in, with the aid of Coulomb drag by the electron current in the graphene-neighboring layer of two-dimensional electron gas in a quantum well [66].

As noted above, Dirac electrons exist not only in graphene, but also on the surfaces of recently discovered new materials — three-dimensional topological insulators [36, 37]. To date, the two- and three-dimensional realizations of topological insulators have been studied. The new paradigm is that topological insulators are not connected with the emergence of spontaneous symmetry breaking in a crystal and, in turn, with its attendant order parameter (as in the case, for example, of magnetics, ferroelectrics, etc.), but with the emergence of a topological invariant in Hilbert space, which is determined by the properties of the Bloch states occupied by electrons. In this sense, there is an analogy between the properties of topological insulators and the quantum Hall effect in which none of the states in the plateau region inside the system are conductive, but at the system boundary there are zero-gap chiral states (a unidirectional current determined by the direction of the magnetic field) protected from the influence of impurities, etc. by the existence of a topological invariant in Hilbert space. This picture is especially simple in sufficiently strong magnetic fields, where the drift approximation applies to electrons and the topological invariant has a simple meaning: it characterizes the connectivity of drift electron trajectories [67]. In three-dimensional (so-called strong) topological insulators, there is a gap in the spectrum of bulk states, as in ordinary insulators, but on the surface they have, owing to the existence of the topological invariant, zero-gap surface electron states with zero effective masses of electrons and holes (as in graphene), which are described by the Dirac equation with a zero mass.

These states are topologically protected: ordinary, nonmagnetic impurities cannot form a gap and localize these states owing to the presence of a topological invariant. One of the important properties of the Dirac equation with a zero mass is a strict connection between the directions of electron momentum and spin (of momentum and pseudospin for graphene).

Owing to a strong spin-orbit interaction, electrons on the surface of a topological insulator possess a strict correlation between the spin and momentum directions: their spin is perpendicular to the momentum, and this property was experimentally revealed by angle- and spin-resolved photoelectron spectroscopy. A similar strict connection between electron momentum and pseudospin (and not spin!) is true for graphene owing to the mathematical equivalence of the Dirac equations with a zero mass for both systems, which this connection follows from.

This connection leads, in particular, to unusual properties of plasmons on the surface of topological insulators (see Refs [68–70]). In quantum terms, a plasmon may be represented as a coherent superposition of excited pairs of electrons and holes shifted in momenta, which correspond for doped graphene to both intraband ($\gamma = \gamma'$) and interband ($\gamma \neq \gamma'$) transitions, so that the plasmon production operator is defined by the linear superposition of the electron production and annihilation operators:

$$Q_{\mathbf{q}}^{+} = \sum_{\mathbf{p}\gamma\gamma'} C_{\mathbf{pq}}^{\gamma'\gamma} b_{\mathbf{p}+\mathbf{q}\gamma'}^{+} b_{\mathbf{p}\gamma}\,,$$

where $\mathbf{p}$ and $\mathbf{q}$ are the two-dimensional momenta.

The plasmon dispersion law can be found by way of linearization of the equations of motion for Dirac electrons, which corresponds to a random phase approximation. The validity of the random phase approximation is defined by the dimensionless quantum parameter equal to the ratio between the characteristic energy of Coulomb interaction and the quantum kinetic energy. For Dirac electrons with a linear dispersion law, this ratio is independent of the electron concentration and is equal to the effective fine-structure constant in which the speed of light is replaced by the electron velocity entering into the Dirac equation for a topological insulator (and graphene), and the charge squared is divided by the permittivity of the surrounding medium. This permittivity is high for topological insulators, and the random phase approximation, therefore, holds true.

Related to the preferential value of plasmon momentum is the preferential momentum of the electrons and holes, which define the plasmon production operator. Because of the strict momentum–spin connection for Dirac electrons, preferential spin emerges as well. Thus, a plasma wave in a topological insulator is always associated with a spin wave! Moreover, an uncompensated total spin polarization emerges in the production of a plasmon (Fig. 2). In the scattering of a spin-plasmon by the nonuniformities of an electric or magnetic field, the angular diagram turns out to be strongly anisotropic and consists of two lobes (Fig. 3).

Interesting effects occur when a magnetic impurity layer or a film of magnetic material is deposited onto the surface of a topological insulator. The external exchange interaction (noninvariant with respect to time reversal) of this layer with Dirac electrons induces a gap in the spectrum of the Dirac electrons, and the topological insulator becomes a quantum magnetoelectric: an external electric field induces (apart from the ordinary electric polarization of the volume) a magnetic moment, while a magnetic field induces an electric

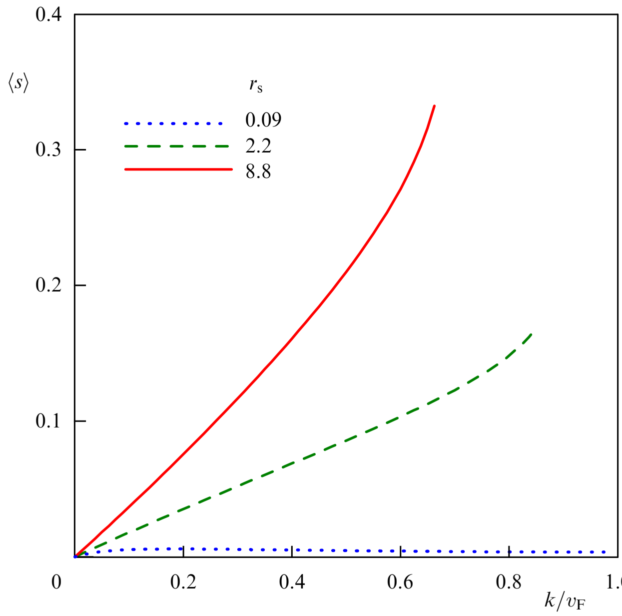

Figure 2. Average value of the spin induced by one plasmon in a two-dimensional Dirac gas on the surface of a topological insulator as a function of its wave vector divided by the Fermi velocity. Parameter r_s is the dimensionless coupling constant for Dirac electrons (the effective fine-structure constant).

dipole moment. This gives rise, notably, to appearing quantized nondiagonal Hall conductivity, and therefore to the quantum Faraday and Hall effect — quantized rotations of the polarization plane of transmitted or reflected electromagnetic waves (in the absence of an external magnetic field!). The chiral properties of the system give rise to chiral properties of the excitons inside the topological insulator gap (dependence of the energy on the sign of angular momentum projection). That is why these chiral excitons make a resonance contribution to the nondiagonal conductivity of the system, which may greatly enhance the Faraday effect in comparison with its quantized magnitude (defined only by the fine-structure constant) (see Refs [71, 72] and references cited therein).

The Coulomb field of the electrons located above the surface of a topological insulator with two-dimensional (2D)

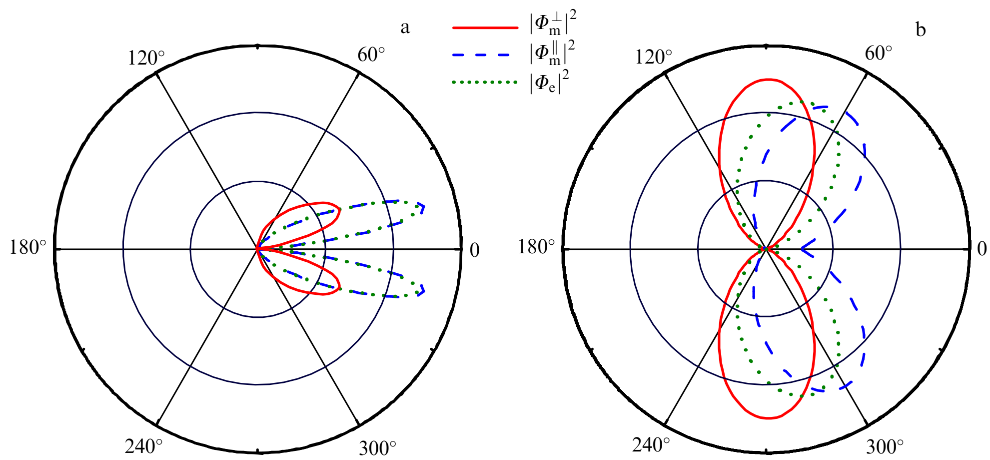

Figure 3. Angular diagram of scattering by nonuniformities of an electric (a) and magnetic (b) field for a spin-plasmon with a momentum $p = 0.2$ (divided by the Fermi velocity). $\Phi_m^{\perp}$, $\Phi_m^{\parallel}$ are the magnetic form factors, and Φ_e is the electric form factor.

chiral electrons induces a magnetic polarization which is equivalent, owing to the symmetry of the problem, to the presence of image magnetic monopoles (similarly to image charges). For a sufficiently dense 2D-electron gas, the emerging total external magnetic field of all the image monopoles may be considered to be uniform and proportional to the surface density of the external electrons and the magnetic monopole charge. This field can manifest itself in the Hall effect for the external electrons and in a change in the dispersion law of their plasma oscillations. For a rarefied system of external electrons, they must exhibit the Aharonov–Bohm effect on magnetic fluxes associated with foreign image monopoles and, therefore, be anions — fractional statistics particles (see paper [73] and references cited therein).

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