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Scientific session of the Physical Sciences Division of the Russian Academy of Sciences (19 December 2005)

A scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) was held in the Conference Hall of the P N Lebedev Physics Institute, RAS, on December 19, 2005. The following reports were presented at the session:

(1) **Krokhin O N** (P N Lebedev Physics Institute, RAS, Moscow) "Electric power transmission using laser radiation";

(2) **Zabrodskii A G** (A F Ioffe Physical-Technical Institute, RAS, St.-Petersburg) "Portable fuel cells: their physics and micro- and nanotechnologies";

(3) **Avrorin E N, Simonenko V A, Shibarshov L I** (Russian Federal Nuclear Center 'E N Zababakhin All-Russia Scientific Research Institute of Technical Physics', Snezhinsk, Chelyabinsk region) "Physics research during nuclear explosions";

(4) **Preobrazhenskii V L** (Wave Research Center of the A M Prokhorov General Physics Institute, RAS, Joint European Laboratory of Nonlinear Magnetoacoustics of Condensed Media (LEMAC)) "Nonlinear acoustics of front-conjugate ultrasonic waves".

An abridge version of the first three reports is given below. V L Preobrazhenskii's report is close in contents to his communication at the session of the Physical Sciences Division of the Russian Academy of Sciences held on 28 September 2005, whose brief presentation was published in the No. 1 (2006) issue of *Physics – Uspekhi* under the Conferences and Symposia heading.

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Electric power transmission using laser radiation

O N Krokhin

This report is concerned with the feasibility of developing an electric power transmission line through the conversion of energy to laser radiation, which is subsequently converted again to electric current employing a semiconductor structure similar to that of a semiconductor laser. The energy is transferred through an optical fiber.

A special feature of the scheme under consideration is the monochromaticity of the radiation converted to electric current and, which is of fundamental importance, the spatial coherence of this radiation. The electric energy loss in such a transmission line can be quite appreciable. However, even today there are grounds to expect a value of no greater than 50% for short distances if use is made of semiconductor structures as the element-converters.

N G Basov and the author of this report drew attention to the possibility of the occurrence of an electromotive force (emf) in the bulk of a semiconductor (similar to gallium arsenide utilized for the production of laser diodes) with a band structure that allows a direct optical transition under high-power monochromatic irradiation [1]. The radiation photon energy should be close to the absorption edge ($\hbar\omega \geqslant \Delta$, where Δ is the band gap) where the absorption coefficient is not too high; otherwise, the semiconductor will be damaged by the thermal shock caused by the high radiation flux applied. The electromotive force arises because the absorption of the light flux increases the electron and hole concentrations to produce a strongly nonequilibrium state which may be described by introducing the concept of quasi-Fermi levels μ_c for the electrons in the conduction band, and μ_v in the valence band, and the magnitude of the emf is defined by the expression $(\mu_c - \mu_v)/e$ (where e is the electron charge).

In the limit of extremely high incoming radiation flux densities, the difference in the quasi-Fermi levels will tend to the photon energy $\hbar\omega$. This state is referred to as the absorption saturation effect and is familiar in quantum electronics.

Apart from monochromaticity, the incident radiation should possess a high spatial coherence, otherwise it will be impossible to concentrate the radiation on the small input window of the semiconductor structure; in other words, this radiation should originate from a laser. This radiation is delivered using an optical waveguide — an optical fiber — which is integrated with the laser source and the structure converting the light energy to electricity. The laser, the converter, and the optical fiber make up a single optical system — a composite resonator.

As is well known, the saturation effect occurs when the optical transition probabilities (the absorption and stimulated emission probabilities) are far greater than the relaxation probability in the quantum system being investigated (two groups of the lower and upper quantum levels). In this case, the absorbed power density asymptotically tends to the energy flux carried to the relaxation channel from a unit volume per unit time. For a semiconductor placed in a strong monochromatic field, the saturation effect reduces, as discussed above, to the asymptotic approach of the energy difference between quasi-Fermi levels of electrons in the conduction and valence bands to the photon energy value. As this takes place, the absorption coefficient, naturally,

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tends to zero. Of course, this all applies to the optical transitions near the absorption edge, i.e., for $\hbar\omega \geqslant \Delta$, because for $\hbar\omega$ appreciably greater than Δ there is no way of approaching the saturation due to a sharp increase in density of electronic states and, therefore, sharp rise in the power density going away through the relaxation channel. Herein, in particular, lies the distinction between the energy conversion scheme under discussion and photoelectric converters (solar batteries) which convert low power densities of light energy. That which we consider in the present report is in essence a scheme akin to a semiconductor laser operating in the inverse order: from light to electric current.

Another significant feature of the scheme being considered is the employment of an optical fiber as the power transmission line, which retains in the ideal case the property of spatial coherence of the electromagnetic wave being transmitted. To put it differently, if a semiconductor laser generates radiation at one end of the fiber-optic line, it has the same brightness at the other end and can be injected into a semiconductor structure with similar geometric parameters, which converts the light energy to electric energy — a converter (Fig. 1). Therefore, the system as a whole comprises a long resonator in which certain light modes are realized. In this case, to lengthen the effective radiation absorption path in the converter, the rear surface of the semiconductor structure can be made totally reflecting. For this purpose, advantage can also be taken of several electrically decoupled sections placed in series to ensure complete absorption of the radiation arriving at the structure or of a multipass scheme.

Let us consider the principle of operation of the monochromatic radiation-to-electric current converter. The device is schematically shown in Fig. 2. The radiation from an optical fiber is fed to a narrow region of the sample with an intrinsic conductivity (i type), which is located between the layers with electron and hole conduction. The optical transition is assumed to be direct, i.e., takes place virtually without a change in electron momentum in the valence band and the conduction band. Figure 3 shows the energy level diagram and the optical transition in the converter. It is

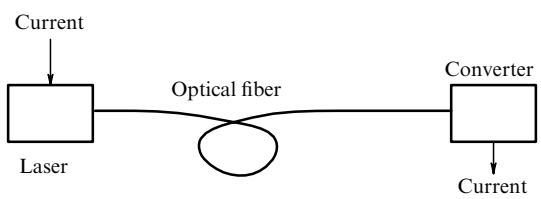

Figure 1. Schematic of the power transmission line.

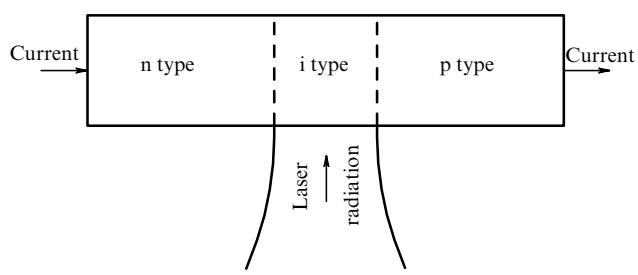

Figure 2. Conceptual sketch of the light-to-current converter.

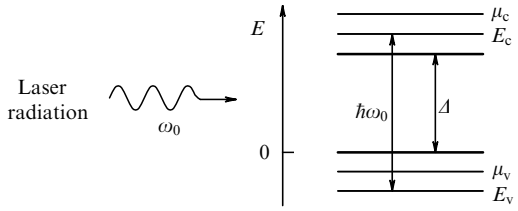

Figure 3. Schematic diagram of electronic levels in a semiconductor. Indicated are direct optical electron transitions between the conduction band and the valence band, as well as the positions of the quasi-Fermi levels in these bands.

assumed that the converter should make use of semiconductor materials, and that in the fabrication of the converter advantage can be taken of techniques similar to those employed in the manufacture of semiconductor lasers.

During the irradiation of a semiconductor by a monochromatic light, there occur optical transitions from the valence band to the conduction band with the absorption of a photon, and transitions in the opposite direction with its stimulated emission. When the incident radiation intensity is low, the relaxation (spontaneous radiative and nonradiative transitions) maintains thermal equilibrium and absorption prevails over stimulated emission, and the valence band will therefore be filled almost completely (if the doping with donor and acceptor impurities is not too high). With an increase in radiation intensity, the population of the levels in the conduction band [equal to the distribution function $f_c(E_c)$, where E_c is the energy level in the conduction band] will rise, and the level populations in the valence band [described by $f_v(E_v)$, where E_v is the energy level in the valence band] will decrease. Therefore, for the absorption coefficient $k(\omega_0)$ we can write the expression

$$k(\omega_0) = \alpha(\omega_0)\left[f_v(E_v) - f_c(E_c)\right], \tag{1}$$

where ω_0 is the incident radiation frequency, $E_c - E_v = \hbar\omega_0 \geqslant \Delta$, and $\alpha(\omega_0)$ is the absorption coefficient for low intensities and low temperature, when the equilibrium carrier concentration is not high and is independent of the radiation intensity, i.e., $f_c \sim 0$, $f_v \sim 1$.

For direct transitions, one has

$$\alpha \sim (h\omega_0 - \Delta)^{1/2}. \tag{2}$$

For highly doped semiconductors, the following estimate is true:

$$\alpha \sim \exp\left[\gamma(\hbar\omega_0 - \Delta)\right], \tag{3}$$

where γ is the parameter, i.e., $\alpha(\omega_0)$ near the absorption edge, where $\hbar\omega_0 \geqslant \Delta$, is proportional to the density of electronic states.

With an increase in radiation intensity, the quasi-Fermi levels of the band electrons begin to shift into the corresponding bands, which manifests itself in the occurrence of nonequilibrium electrons in the conduction band, and vacancies (holes) in the valence band. At very high intensities, when the relaxation rates are relatively low, the energy difference between the quasi-Fermi levels in the conduction band, μ_c, and in the valence band, μ_v, asymptotically tends to $\hbar\omega_0$:

$$\mu_c - \mu_v \to \hbar\omega_0 .$$

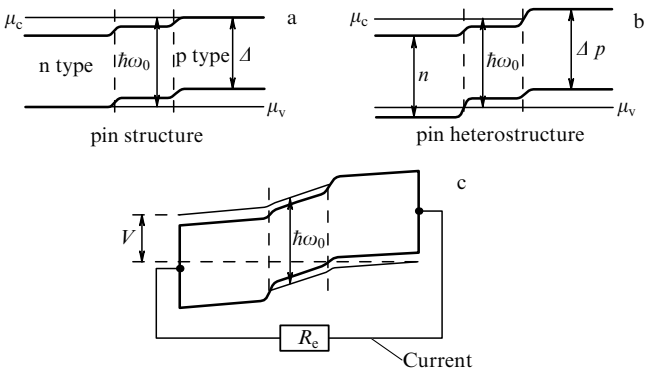

Figure 4. Energy structure of a semiconductor converter: (a, b) 'idle' mode, and (c) operation under a load R_e; V is the electric voltage; pin structure: p region, undoped i region, and n region arranged in series.

Upon substituting into formula (1) the expression for the Fermi distribution function

$$f(E) = \frac{1}{\exp\left[(E-\mu)/T\right]+1}\,, \tag{4}$$

expression (1) can be rewritten as (see Fig. 4)

$$k(\omega_0) = \alpha(\omega_0)\,\frac{1}{\exp\left[(E_v-\mu_v)/T\right]} \times \left\{1 - \frac{1}{\exp\left[(\hbar\omega_0-\mu_c+\mu_v)/T\right]}\right\}, \tag{5}$$

whence it follows that $k(\omega_0) \to 0$, when $\mu_c - \mu_v \to \hbar\omega_0$.

The number of ingoing radiation quanta absorbed in a unit volume in a unit time is determined by the equation

$$-\frac{\mathrm{d}I}{\mathrm{d}x} = k(\omega_0)\,I\,,$$

where I is the photon flux per unit surface area (the intensity). One can see from relationship (5) that the absorption saturation effect becomes appreciable when $\hbar\omega_0 - \mu_c + \mu_v \leqslant T$. This circumstance permits expansion of the expression on the right-hand side of formula (5) in terms of the small quantity $(\hbar\omega_0 - \mu_c + \mu_v)/T$ to obtain as a crude approximation the expression

$$k(\omega_0) = \alpha(\omega_0)\,\frac{\hbar\omega_0-\mu_c+\mu_v}{T}\,\frac{1}{\exp\left[(E_v-\mu_v)/T\right]}\,, \tag{6}$$

where the last term on the right-hand side appears because the effective electron masses in the conduction and valence bands (the effective masses of electrons and holes) are not equal.

The quantity $f_v(E_v) - f_c(E_c)$ can be determined in the stationary case from the equality condition for the absorption rate $|k|I$ and the electron–hole recombination rate $R(n,p)$, i.e., the relaxation rate, per unit volume:

$$|k|I = R\,. \tag{7}$$

For high levels of the nonequilibrium concentrations of electrons, n, and holes, p, the recombination rate is proportional to their product. If advantage is taken of the simplified expression (6) for the absorption coefficient, formula (7) can be rewritten as

$$\hbar\omega_0 - \mu_c + \mu_v \approx \frac{TR}{\alpha(\omega_0)I}\,\exp\left(\frac{E_v-\mu_v}{T}\right), \tag{8}$$

whence it follows that the difference $\mu_c - \mu_v$ approaches $\hbar\omega_0$ for high intensities.

Therefore, an electromotive force arises in the absorption region. To realize it in the form of electric current requires that the electrons and holes should move in the opposite directions. This can be achieved by attaching the highly doped semiconductors with n- and p-type conduction to either side of the absorption volume. Upon connection of a load, the electrons will then drift to the n region, and the holes to the p region under the action of the field in the active region (see Fig. 4).

To reduce the losses due to the drift of electrons to the n region, and of holes to the p region, use can be made of a heterostructure which sets up additional barriers for respective electrons and holes. In this case, the resultant electric current 'loads' the volume in which the production of electron–hole pairs occurs, and formula (7) can be rewritten in the form

$$kI = R + \frac{J}{de}\,, \tag{9}$$

where J is the electric current density, and d is the thickness of the layer in which the electron–hole pair production takes place.

The parameters of such an electric power transmission line can be estimated by drawing an analogy to the recently developed devices and elements — semiconductor lasers and optical fibers. A single semiconductor laser can provide an output power up to 10 W with a very high efficiency of about 70% [2]. The emitting window of this laser measures 1×100 μm, i.e., the power density amounts to 10 MW cm^{-2}. This is a very high value. A light power density below 1 W cm^{-2} is converted in solar batteries. Since the converter of light energy to electric current is close in design and manufacturing method to semiconductor lasers and constitutes actually a laser operating in inverse order, one might figure on equally high conversion coefficients in the future. Modern optical fibers are capable of transmitting substantial light fluxes of over 100 W and possess very small attenuation coefficients on the order of 0.1 dB m^{-1} [3].

Therefore, the proposed scheme enables transmission of the electric power for a short distance with a transfer coefficient of 50%. It is pertinent to note that the case in point is a low-voltage transmission line with a voltage around that of the semiconductor band gap. The distinction between the converter under consideration and the widely used photoelectric cell (which offers a very high efficiency) consists in the fact that advantage is taken of the spatial coherence of laser-generated radiation. This makes it possible to realize a high power density at the converter input, so that the converter dimensions turn out to be small in comparison with the dimensions of ordinary photoelectric cells.

It is likely that there is good reason to fabricate the converter in the form of a layer structure in which the radiation sequentially passes through several layers to experience gradual absorption, the layers being electrically connected in series. Such a converter will then yield a higher voltage at its output.

To summarize, the method of electric energy transfer considered in the present report may turn out to be beneficial in low-voltage transmission lines or in other cases where there exists unwanted extraneous electrical noise in transmission lines or circuit commutation devices. Furthermore, it can be employed when there is no way of applying metal conductors (for instance, in high-voltage devices) or when decreasing the weight characteristics of supply lines becomes a paramount requirement.

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Portable fuel cells: their physics and micro- and nanotechnologies

A G Zabrodskii

1. Introduction

This report presents a brief review of the results of investigations carried out at the A F Ioffe Physical-Technical Institute (PTI) and at a number of other institutes of RAS in one of the branches of hydrogen power engineering, dealing with the development of portable fuel cells.

Actually, research in the field of energetics is a traditional topic for the Petersburg Physical-Technical Institute. It was here that Ioffe created the national scientific school of thermoelectricity and began the practical implementation of this effect for cooling. In the 1930s, nuclear studies were launched in a laboratory headed by I V Kurchatov with Ioffe's support. There the young scientists G N Flerov and K A Petrzhak discovered spontaneous uranium fission. At the beginning of the Great Patriotic War (1941 – 1945), Flerov was studying at a school for aircraft technicians, where he wrote his well-known letter to I V Stalin, in which he stressed the immediate need to begin work on the atomic bomb. This event marked the beginning of the Soviet Atomic Project and the birth of the nuclear power industry, to which the researchers at PTI contributed greatly. It was at PTI that V N Tuchkevich as a scientific leader and his colleagues developed a new area of research — high-current semiconductor electronics. Studies in highly effective solar power engineering based on the use of semiconductor heterostructures may be highlighted as an outgrowth of the backbone area of research in physics, engineering, and technology developed at PTI by Zh I Alferov and the scientific school he created in the field of semiconductor heterostructures. For more than half a century, the PTI staff has participated in physics research programs, in developing technologies associated with controlled fusion based on tokamaks, and in the diagnostics of hot plasma. Several years ago, an entirely new spherical tokamak 'Globus-M' became operational at PTI and physical investigations began on it.

Relatively recently, PTI became actively involved in hydrogen power research within the program that incorporated RAS and the Norilsk Nickel Mining and Smelting Co. (later the program gave birth to the National Innovation 'New Energy Projects' Company). Here I will speak only of works dealing with the development of new types of portable fuel cells. The material I will present illustrates the typical approach to research at PTI: from scientific investigations to basic technologies and later to the development of new facilities. The basic technologies in this field are those involving the deposition of monodispersed nanocatalysts (Section 3) and also silicon micro- and nanotechnologies (Section 4) utilized to develop portable fuel cells (Section 5). I will also discuss possible ways of raising the efficiency and specific power of fuel cells (Section 5). Minimum information about hydrogen energetics and fuel cells is given below in Section 2.

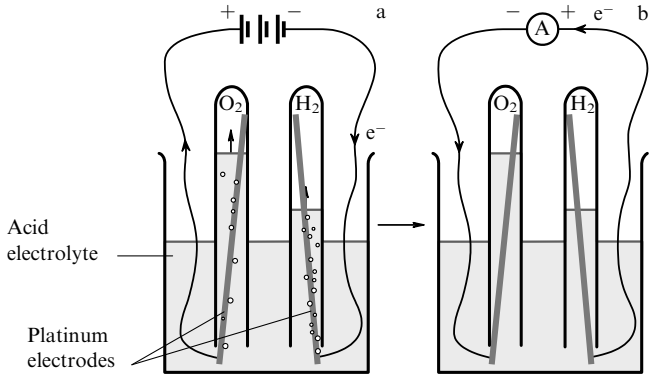

Figure 1. An electrochemical cell operating in the electrolysis mode (a), and in the fuel-cell mode (b).

2. Hydrogen power engineering and fuel cells

The interest in generating power through the use of hydrogen is stimulated by the gradual depletion of fossil fuel reserves [1] and by ecological problems, as well as by the need to raise the efficiency of energy conversion.

What makes hydrogen so attractive as an energy carrier is, on the one hand, the great variety of sources for its production, among which are coal, natural gas, biomass, solar energetics, thermal energetics, photoelectric power engineering, hydroelectric power engineering, wind energy, nuclear electrical power engineering (the last four via electrolysis), and nuclear thermal power engineering. On the other hand, the merits of hydrogen manifest themselves most vividly when it is used as an energy carrier in key devices of hydrogen power engineering, namely, fuel cells of various types, which encompass a broad spectrum of power outputs: from several dozen milliwatts to several megawatts.

The first fuel cell was developed by William R Grove of Great Britain in 1839 already. His device produced electric current from hydrogen and oxygen reacting at platinum electrodes (Fig. 1 [1]). When an external source of electricity

[1] Note that our ideas about the depletion of oil reserves are basically formed by the rising prices for crude oil and petrol. These prices strongly depend on inflation of world currency and political stability in the main regions of oil production. A sharp increase in oil prices usually accompanies political upheavals and wars in such regions. The absolute record in oil prices with inflation taken into account was not reached in recent years but on the verge of 1970s and 1980s when the Iranian Revolution took place. Nevertheless, the very fact of substantial depletion of reserves of natural fuel, primarily crude oil, is indeed true and is certainly a troubling problem for the oil (and gas)-importing countries.