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A material with a high threshold for breakdown under electric field and with an optically switched permittivity

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Introduction

In this note we describe the properties and composition of a material for the development of a laser-assisted source of electromagnetic radiation. We are interested in the possibility of obtaining radiation fields near the surface of the material of the order of 1 GV/m (as our ultimate goal). Thus, we need a material that is capable of holding ~1 GV/m without breakdown. At the same time we want to illuminate the material with a short and low energy density laser pulse and produce a significant change in the permittivity of the material. This latter process will give rise to radiation of the electrical energy "stored" in the material. We estimate that ~ 10^4 – 10^5 times more energy can be radiated in the infrared region than it is carried in the laser pulse used to trigger the radiation.

At the end of this note we show that a desirable composition for this new material is somewhat similar to the composition of low pass optical filters. Thus, the latter can be used for proof-of-principle tests.

Properties of the material

According to Ref. [1] the breakdown field in different glasses in a static homogeneous electric field is ~ 0.5 GV/m. The threshold must be higher when the electric field is applied only for a short time ~ 1 ns [2]. By doping the glass with semiconductor additives one can prepare a material whose permittivity can be affected by the laser light. We consider small sized semiconductor crystallites with a more or less spherical shape distributed over the entire glass with a relatively high density and uniformity. The size of the crystallites must be smaller than the laser wavelength to prevent a significant diffusive scattering of the laser light. Additionally, and more importantly the size of the crystallites and the band gap of the semiconductor should be specifically chosen to reach a condition when crystallites will hold ~1 GV/m during a short time ~ 1 ns. The recipe showing how to reach this goal is described below.

Let us assume that the crystallites comprise a fraction, p, of the volume of the material and that they are more or less uniformly distributed over the entire volume. For the sake of simplicity we also assume that the electric permittivity of the semiconductor is approximately the same as electric permittivity of the glass that holds the semiconductor crystallites. Illumination by a short laser pulse at a frequency corresponding to a band gap of the semiconductor makes the crystallites conductive. A rapid change of their conductivity in a large fraction of the volume of the material must result in a significant and a rapid change of the permittivity of the material. The latter

causes radiation of the electromagnetic field. The magnitude of the radiated energy can be estimated using the following expression:

$$W \approx \frac{E^2 V}{2}\frac{\Delta\varepsilon}{\varepsilon} = \frac{E^2 V}{2} p, \qquad (1)$$

where W is the intensity of the radiation field, E is the electrostatic field in the bulk of the material, V is the volume of the material illuminated by the laser light, ε is the electric permittivity of the material and $\Delta\varepsilon = \varepsilon p$ is the variation of ε caused by the laser light.

Now we are going to discuss what needs to be done to ensure that the semiconductor crystallites will hold the field ~ 1 GV/m for ~ 1ns. We assume that the avalanche process in a high electric field will inevitably cause an electric breakdown over an entire volume of a semiconductor wherever a single electron or a single hole appears in a conductive/valence band of the semiconductor during the time of a high voltage pulse. Therefore, the approach we are taken consists of restricting the volume available for avalanche development by using semiconductor crystallites with small size. Additionally, we chose a semiconductor material with a low probability for electrons/holes to be in the conductive/valence band in a crystallite of a given volume.

An electron in a conducting band and a hole in a valence band may appear in a strong electric field via the process of pair creation (tunneling effect). The average rate of these events, $\dot{n}$ ($cm^{-3}s^{-1}$), can be estimated using the expression:

$$\dot{n} = \frac{1}{(2\pi)^2}\left(\frac{m^*}{m}\right)^{-7/2}\frac{c}{\lambda_c^4}\left(\frac{mc^2}{2\Delta}\right)^{1/2}\left(\frac{E}{E_0}\right)^2 \mathrm{Exp}\left(-\frac{2}{3}\sqrt{\frac{m^*}{m}}\frac{E_0}{E}\left(\frac{2\Delta}{mc^2}\right)^{3/2}\right). \qquad (2)$$

where m is the electron mass, m^* is the effective electron mass in the semiconductor, c is the speed of light, λ_c=3.86x10^{-11}cm is the Compton wavelength of the electron, Δ is the gap of the semiconductor, and $E_0 = \frac{e}{r_e \lambda_c}$=1.3x$10^9$ GV/m. Using E=1 GV/m and taking a volume of ~10^{-15} cm^3 (a linear dimension ~ 0.1 micron), time interval of ~1 ns, and assuming a semiconductor with $m^* \approx 0.8\ m$ and $\Delta \approx$3.0 eV, we find the probability for a pair creation of ~10^{-3}. It means that in this example only one out of every thousand crystallites will break down. As a result we will notice only ~ 0.1% reduction in the radiation energy. We would like also to emphasize the importance of the semiconductor gap and effective electron mass in a semiconductor because of the strong dependence of $\dot{n}$ on Δ and m^*. For example ~15% reduction in Δ will result in the probability for an electron in a conducting band and a hole in a valence band to go up from 10^{-3} to 1.

The probability, $\dot{n}$ ($cm^{-3}s^{-1}$), for electrons to appear in a conductive band because of the finite temperature of the material is ~10^{11} times less than due to a pair creation. It follows from a calculation using the formulae:

$$\dot{n} = \frac{N_A \rho}{A\tau}\mathrm{Exp}\left\{-\frac{\Delta}{2kT}\right\}, \qquad (3)$$

where N_A is the Avogadro constant, ρ is the semiconductor density, A is the atomic weight of the semiconductor, k is the Boltzmann constant, T is the temperature, and $\tau \sim 10^{-13}$ s is the relaxation time ($\tau \sim \ell / v$), where ℓ is the mean free path of the electron in the conductive band, and $v \sim 10^7$ cm/s is an average electron velocity at room temperature.

The above expression is written for a pure semiconductor. However, impurities with different ionization energies may have higher probabilities for electrons in a conductive band. Thus, it is necessary to have a sufficiently pure semiconductor so that the probability for electrons in a conductive band of a single semiconductor crystallite due to impurities will be less than 10^{-3}.

So far we were concerned that a single electron in the conductive band of the semiconductor will start the avalanche process that will result in a complete turnover of a semiconductor into a conductive state. On the other hand, we prefer this situation because just a single photon per crystallite creating the electron in a conductive band will trigger a transition of the crystallite into a conductive state. This would imply a significant saving of the laser pulse energy compared to the case when all the electrons in a conductive band are produced by laser photon absorption. The enhancment factor, g, can be estimated as follows:

$$g \approx \frac{E r^2}{5e}, \tag{4}$$

where r is the crystallite radius, e is the electron charge, and the calculation must be carried out in CGS units for all parameters. In the above expression we assume that in average ~5 photons per crystallite will be needed to insure that each crystallite in the material gets at least one photon with high probability. Using r=100 nm, E=1 GV/m, we calculate $g \approx 4 \times 10^5$.

Another important parameter is the ratio of the radiated energy to the laser pulse energy, η. It is equal to:

$$\eta \approx \frac{3}{20\pi} \frac{E^2 \delta V}{\Delta}, \tag{5}$$

where δV is the volume of the crystallite. Here we also assume ~5 photons per crystallite. Using $\delta V = 10^{-15}\text{cm}^{-3}$, E=1 GV/m, and $\Delta \approx 3.0$ eV, we calculate: $\eta \approx 10^4$.

Applications and critical issues

The material described above may find applications in the design of a high energy-gain accelerator or/and an electron gun with an ultra low electron beam emittance. It can also be considered for the generation of far infrared radiation.

Semiconductor-doped glasses, being known as low pass optical filters, have many similarities with the material discussed above. According to Ref. [3], the filter glass contains cadmium sulfide (CdS) crystallite. The size distribution is between 10 and 50 nm. The band gap values depends on the crystalline composition and size. When crystallites are small the energy levels are separated by a value larger than it is in the bulk material and the observed cut-on wavelength is shifted to the blue.

We propose to use this material for proof-of-principle experiments. The first experiment could be a demonstration of the radiation in a simple configuration shown in Figure 1 and carried out with a relatively low-bias electric field. We estimate that it should be possible to radiate ~ 10^{-7} J/cm^2 at ~ 1 mm with a bias field of ~10 kV/cm. Of course, this experiment will not take the advantage of the avalanche process in a high electric field and all the electrons in a conductive band will be created by laser photon absorption.

Next step could be an extension of the first experiment to an experiment with a structured antenna shown in Figure 2. This will require preparation of electrodes in an interdigitated geometry, covering every other electrode with a nontransparent material for the laser light. All this will allow increasing the radiation energy.

Another important direction of research is a study of the mechanisms of the electric breakdown and obtaining the ultimate electric fields. This research will require a high voltage pulse generator with a pulse duration ~1ns.

For a variety of applications materials with different volume densities of crystallites and with crystallites of different sizes may be needed. These needs should also be addressed.

Finally, it is not necessarily true, that the glass is the best medium for the considered material. Therefore, a search for a better medium must be carried out.

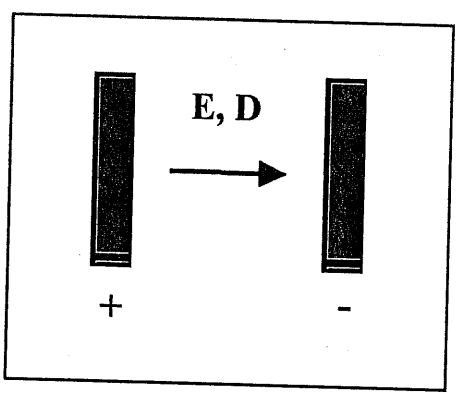

Fig. 1 A schematic of the experiment for a demonstration of the radiation.

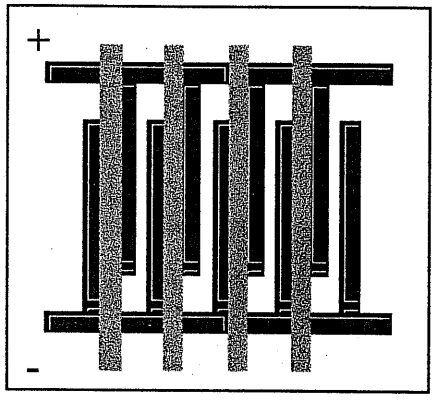

Fig. 2 A schematic of an antenna for a high field radiation.

References

[1] B. M. Tareev, et. al., "*Electro and radio materials*", Moscow, 1978, (in Russian).

[2] F. Villa, private communication, 1993.

[3] R. J. Scheller, Schott Glass Technologies Inc., private communication, September 1999.