Fast bolometric sensor built-in into polycrystalline CVD diamond

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Abstract. Diamond, with its unique combination of physical properties, is a promising material for electronic devices operating under extreme conditions. Due to its exceptionally high thermal conductivity, diamond-based bolometers should possess very short response time. A fast bolometric sensor was formed within a polycrystalline diamond plate by ion implantation and subsequent annealing. The response kinetics of the structure was studied under a nitrogen laser pulsed illumination. The response time at room temperature was less than 20 ns. The spatial-temporal distribution of responses allowed us to distinguish between thermal responses and those of different nature (e.g. photoconductivity). This study was supported by the Russian Foundation for Basic Research, project nos. 05-02-17545 and 07-02-00575.

1. Introduction

Diamond is a most appropriate material for use in electronic devices and as a base element for electronics and scientific equipment (substrates, radiation-resistant detectors of ionizing radiation, and windows in chambers, cryostats, lasers, and gyrotrons) under extreme conditions. Such conditions are, e.g., elevated temperatures, aggressive environment, and high-density radiation fluxes with photon energies up to the x-ray range, as well as high-energy particle fluxes.

Due to the record high thermal conductivity of diamond (up to 24 W/cm·K), bolometers with diamond-based resistive elements exhibit a fast response. In [1], the development and fabrication of a bolometric sensor based on a layer that was produced in the bulk of a type-IIa natural diamond by ion implantation and subsequent graphitization was reported. It is clear that such a sensor embedded in a material minimizes all the disadvantages inherent to sensors attached to an object being measured. Nowadays CVD diamond is an available construction material with properties close to those of natural diamond. In this paper, we report on the development of a bolometer based on a polycrystalline diamond grown by chemical vapor deposition (CVD).

Polycrystalline diamond films feature a columnar structure of grains (with the grain axis directed normally to the film surface), which results in an appreciable anisotropy of the thermal conductivity along and across the growth direction [2]. Therefore, it is not clear a priori how bolometers based on CVD-grown and natural diamonds will differ in terms of their response to laser irradiation. Moreover, the fabrication of a sensitive conductive layer of the bolometer implies high-temperature annealing (above 1400°C) of an ion-implanted sample. This annealing results in graphitization of the grain boundaries in CVD diamond and in the formation of graphite islands in the bulk of crystallites [3]. For
this reason, the problem of the influence of the interfaces between grains in a CVD-grown diamond film on the response of the fabricated structure to laser excitation likewise requires experimental study.

2. CVD diamond and bolometric structure

The diamond sample used to fabricate a bolometer was a transparent plate that was polished on both sides and measured 3×7×0.46 mm in size. An initial plate of polycrystalline diamond 57 mm in diameter and 0.55 mm in thickness was grown on a silicon substrate from a gas mixture of methane and hydrogen in a microwave discharge in an UPSA-100 plasmachemical reactor [4]. Then, the silicon substrate was removed by chemical etching and the sample to be studied was cut out from the CVD diamond plate using a laser. The size of randomly oriented diamond crystallites on the growth side was 70–110 µm. The 50-µm-thick fine-grained layer adjacent to the substrate was removed by grinding.

The room-temperature thermal conductivity measured along the plate was $k_{||}=19.1$ W/cm·K, and in the direction perpendicular to the plate plane was $k_{\perp}=22.8\pm1.7$ W/cm·K. The difference between $k_{||}$ and $k_{\perp}$ is due to the fact that the phonon scattering rate at grain boundaries during phonon propagation across columnar crystallites ($k_{\perp}$) is higher than that in the case where phonons propagate along these crystallites ($k_{||}$). Thus, the thermal conductivity anisotropy $(k_{\perp}-k_{||})/k_{\perp}$ is about 16%, which is typical of textured diamond films [4]. The above values of the thermal conductivities are close to those characteristic of the most perfect nitrogen-free diamond single crystals ($k=20–24$ W/cm·K).

A bolometer based on a buried graphitized layer was fabricated by implanting a diamond plate by 350-keV C$^+$ ions with a dose of $8\times10^{15}$ cm$^{-2}$. The contacts to the buried layer were graphite columns (columns 2 in Figs. 1a, 1b) fabricated by implanting C$^+$ ions with an energy distribution from 350 to 20 keV. After 1 h of annealing in vacuum at 1500°C, a set of sensitive elements (bolometers) 70 and 300 µm long was formed on the basis of the buried graphitized layer embedded in the CVD diamond bulk. Under the technological conditions used, the layer was located at a depth of 265 nm and its thickness was 220 nm (layer 1 in Figs. 1a, 1b).

The temperature dependence of the resistance of the bolometers under study is linear in the temperature range 230–380 K, with the temperature coefficient of resistance being $–1.47\times10^{-4}$ K$^{-1}$. The room-temperature bolometer resistances range from 300 to 1200 Ω depending on the length of the sensitive element.

3. Results and discussion

We measured the response of the structure to irradiation by a pulsed nitrogen laser ($\lambda=337$ nm, $\tau_{d}=8$ ns). The experimental setup used allowed scanning of the sample front surface by a laser beam focused onto a spot 80–90 µm in size. The time dependence of the response was measured at any chosen position of the beam.

We found out that the most intense response is observed when a laser beam falls immediately on a sensitive element (points A and B on figure 1a). However, at times of 0–15 ns, the response also exists.
when a laser beam is incident on the area between contacts where the buried graphitized layer is absent (for example, point C on figure 1a). This response is smaller in amplitude by a factor of 3 to 5 than that of the bolometer itself and is much shorter in time. Such responses were also observed in an analogous structure involving only graphite columns without a graphitized layer between them and on a virgin CVD diamond plate not exposed to ion implantation and high temperature annealing. It means that this “fast” response is caused by the diamond bulk photoconductivity, but not by the thermal induced conductivity change of grain boundaries, which could be graphitized during annealing.

Figure 2 shows the time-resolved bolometer responses obtained when the buried graphitized layer is exposed (point A, curve 1) or when a laser beam is incident on the area between contacts that is remote from the layer (point C, curve 2), as well as the difference response obtained by subtracting curve 2 from curve 1, i.e., namely the thermal component of the bolometer response (dotted curve).

To calculate the thermal component of the response, the space–time distribution of the bolometer temperature should be determined. We simulated the bolometer using a three-layer structure (see insert in figure 3). The spatial distributions of the temperature were calculated in the axisymmetric geometry by solving the set of three heat conduction equations (see [5] for details).

Figure 2. Experimental bolometer responses to irradiation of the bolometer itself (1) and the area between contacts (2). The difference response (dotted curve).

Figure 3. Comparison of the experimental (circles) and calculated (solid curve) bolometer responses. On the insert – calculation model geometry (schematic).

Layers 1 and 3 correspond to the diamond matrix, the specific heat $c_1,3 = 522$ J/kg-K and the density $\rho_1,3 = 3500$ kg/m$^3$ were taken from [6], and the thermal conductivity was assumed to be anisotropic ($\kappa_{1,3} || = 19.1$ W/cm-K and $\kappa_{1,3} \perp = 22.8$ W/cm-K). Layer 2 corresponds to the graphitized layer; its parameters were initially set equal to those of pyrolytic graphite [7] and then were varied to achieve the best fit with the experimental data. Light absorption in the graphitized layer was assumed to obey the Bouguer law, and the absorption constant was measured to be $\alpha = 3.3 \times 10^7$ m$^{-1}$.

In addition, we analyzed the possible influence of the thermal conductivity anisotropy of the CVD diamond plate on the response of the system under the conditions of our experiment. The thermal conductivity $\kappa_{1,3} \perp$ was taken equal to 22.8 W/cm-K, and $\kappa_{1,3} ||$ was varied from $\kappa_{1,3} \perp$ (absence of anisotropy) to 0.2$\kappa_{1,3} \perp$ (strong anisotropy). It appeared that a change in the anisotropy of the thermal conductivity within these limits has almost no effect on the time dependence of the response. This is due to the fact that the laser excitation spot size (~90 µm) is large in comparison to the diamond heating depth $L_* = (\kappa_1 || \tau / c_1 \rho_1)^{1/2} = 11$ µm for the characteristic response time $\tau \leq 100$ ns; therefore, the heat propagation is one-dimensional.

By varying the value of the thermal conductivity of the graphitized layer, we fitted the calculated response (figure 3, solid curve) to the thermal component of the experimental response (open circles). The fitted value of the thermal conductivity of the graphitized layer was found to be $\kappa_2 || = \kappa_2 \perp = 0.082$ W/cm-K. This value is larger than that for amorphous carbon ($\kappa \approx 0.016$ W/cm-K) [8] and
close (in order of magnitude) to the thermal conductivity of polycrystalline graphite annealed at 1500°C ($\kappa \approx 0.1 \text{ W/cm-K}$). This fact probably suggests that annealing causes only partial crystallization of the initially disordered implanted region.

It is worthwhile to mention, that both sensitivity and temporal parameters of the bolometer developed were similar to those of the bolometer based on natural IIa type diamond [1]. In a figure 4 response to the laser excitation, measured by the bolometer on the basis of natural diamond is compared to that measured by the bolometer based on CVD diamond. One can see a good coincidence.

![Figure 4. Comparison of the bolometer responses measured on CVD (solid) and natural IIa type diamond (dashed).](image)

4. Conclusion
Preliminary measurements of the bolometric structure response to laser irradiation allow us to conclude that embedded graphitized layers can be used to produce fast (in the nanosecond range) bolometers for controlling temperature conditions in elements of diamond electronics and for detecting radiation with high time resolution, as well as, e.g., to develop pulsed sources of IR radiation with Joule heating.

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