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Neutron Radiation Effects on Thin-Film and Two-Dimensional Magnetic Field Sensors

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Summary:

Reporting research findings on two types of magnetic field sensors for use in harsh environments and the impact of high-energy neutron flux on them. Researched sensors being 2-D epitaxially grown quasi-free-standing graphene on SiC and thin film InSb on GaAs. The research constitutes a continuation of the series of studies assessing the radiation resistance of graphene-based sensor platforms compared to classical thin-film magnetic diagnostic systems.

Keywords: Hall effect sensor, radiation-resistance, self-healing, magnetic diagnostic, neutron irradiation

Introduction

There has been an increasing interest in the development of magnetic field diagnostics in recent years, especially in sensors that can operate under harsh environments. These applications include aerospace, defense, and particularly the energy industry. The use of controlled nuclear fusion as an energy source of the future remains one of the greatest endeavors of our century [1]. To monitor thermonuclear processes, a complex sensor infrastructure is required. For magnetic fusion confinement, which is the most promising fusion technology, magnetic field sensing is one of the most crucial diagnostic elements. This field however still requires development since the sensing electronics will operate for an extended period under fast neutron radiation and high temperatures. Unfortunately, it has proven to be an incredibly difficult task, thus research into the most effective sensing platforms is still ongoing [2],[3].

Our research focuses on two magnetic field sensors with potential use in the energy industry: a semiconductor, thin film InSb-based and a 2-D, epitaxial graphene-based on silicon carbide (G@SiC) sensor. Both of these sensors have proven to be effective in temperatures up to 350 °C and fast neutron radiation fluence of 0.7×10^{18} cm^{-2} [4]. It has also been shown that any changes in irradiated graphene-based sensors' performance were caused by neutron radiation and not the impact of high temperatures [5]. In this research, we aim to show new findings on the effects of 3 times greater fast neutron fluence and the impact of a different polytype of silicon carbide substrate in graphene-based sensors.

Methods and materials

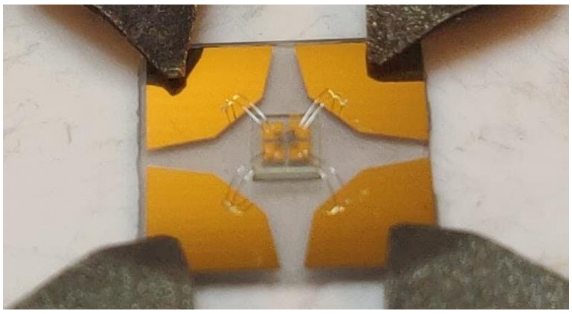

Fig. 1. Optical image of the G@SiC sensor. The sensing part is centrally placed and is connected to electrode plates to ease manual manipulation.

We present here two types of Hall effect sensors. First, a 2D-material in the form of hydrogen-intercalated quasi-free-standing graphene on a semi-insulating SiC substrate, passivated with an Al_2O_3 layer [6], which is visible in Fig.1. The sensors were fabricated on either 4H-SiC (0001) or 6H-SiC (0001) substrate. The other structure was prepared in the form of donordoped InSb-based thin-film on a semi-insulating GaAs substrate [4]. The tested systems were exposed to a fast neutron fluence of 2×10^{18} cm^{-2} using the MARIA research nuclear reactor in Poland.

After irradiation, the sensors' electrical parameters were measured during annealing cycles following the method described in [5].

Results

For graphene-based structures after irradiation, we theorize that the main factor affecting the electrical parameters is the loss of atoms in the hydrogen layer, based on Hall effect measurements and micro-Raman characterization. We anticipate that temperatures above 200°C will facilitate the diffusion of the hydrogen atoms from parts with higher to lower concentrations. This effect can reduce the surface area where intercalation is too low to support the separation of the graphene [4].

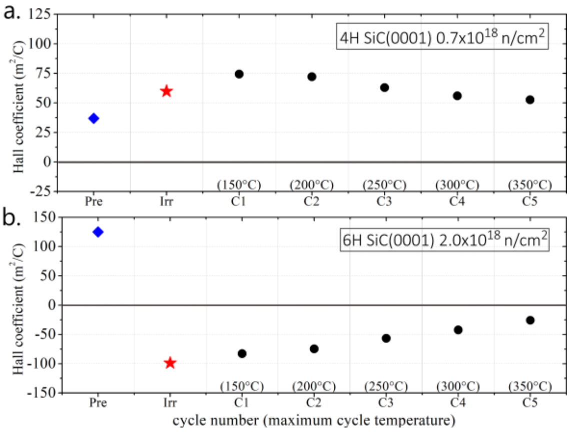

Fig. 2. The comparison of Hall coefficients of G@SiC on 4H and 6H SiC substrates. Blue squares represent measurements before irradiation, the red star measurements after irradiation, and each black dot is a room temperature measurement after the annealing cycle.

Fig. 2a shows the dependence of the Hall coefficient measured for a sensor irradiated in the neutron fluence of 0.7×10^{18} cm^{-2}. This graph was made based on the data from [4], [6] and is the starting point for the next experiment of irradiating the system with neutron fluence of 2×10^{18} cm^{-2}. Fig. 2b shows an analogous line of Hall coefficient changes before and after the experiment.

From the comparison of the obtained results, we can draw further conclusions about the destructive effect of the high-energy neutron flux on the G@SiC system. The Hall coefficient immediately after irradiation (comparison of red and blue points) changed sign in the case of the 6H sample (neutron fluence of 2×10^{18} cm^{-2}), which indicates a change in the type of conductivity of the system and may suggest excessive depletion of H intercalation or the influence of the 6H substrate. The nature of the changes after successive thermal cycles (trend of black circles) is also different. The presented studies based on Hall effect measurements will be complemented by micro-Raman analysis, which will be able to show the degree of defection of the graphene layer itself, thanks to which conclusions can be drawn about the radiation resistance of the entire graphene-based chip.

The results suggest the superiority of 2-D active layers over thin-films in terms of resistance to high energy neutron radiation.

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