UV Sensor Based on Layered Ferrite-Diamond Structure

P Y Belyavskiy1, A V Kondrashov1,2, A A Nikitin1,2, V V Vitko1,2, B A Kalinikos1, A A Semenov1, A B Ustinov1 and J E Butler3

1St. Petersburg Electrotechnical University, St. Petersburg, 197376, Russia
2Institute of Applied Physics of the Russian Academy of Science, Nizhny Novgorod, 603950, Russia
3Cubic Carbon Ceramics, Huntingtown, MD, 20639, USA

E-mail: pbeliavskiy@gmail.com

Abstract. Design of a UV sensor based on an yttrium-iron garnet/diamond layered cavity is presented. The operation principle of the sensor is based on the change in the spin-wave dispersion law and, consequently, in the frequency and Q-factor of eigenmodes of the cavity under study upon appearance of free carriers generated by UV light.

One of ways to improve the resolution of the photolithographic process is to use far-UV light with wavelengths of 157 to 248 nm [1]. Improving the characteristics of fast and sensitive far-UV sensors will enable wider mastering of this spectral range.

One of ways to develop a sensor for far-UV emission is to use a material with an energy gap width comparable with the energy of a UV photon. One of materials of this kind is single-crystal diamond whose energy gap width is about 5.5 eV. Recent advances in the fabrication technology of single-crystal films and layers of diamond with varied doping level open up prospects for their use as sensors for light with wavelength shorter than 250 nm. For example, emission sensors constituted by single-crystal diamond with metallic electrodes were suggested in [2--5].

In this communication, we suggest a simple UV sensor design based on an yttrium-iron garnet/diamond layered structure. The operation principle of microwave devices based on single crystal yttrium-iron garnet (YIG) films magnetized to saturation is underlain by specific features of the propagation in these devices of a particular kind of waves: magnetization waves or long-wavelength spin waves [6]. The operation principle of the UV sensor we suggest is based on the effect of free carriers generated in the semiconductor on the dispersion law of spin waves (SWs) in the YIG film.

The effect of conducting screens on the dispersion characteristics of SWs has been studied in sufficient detail. In particular, a dispersion equation for the surface SW in a film with a metallic screen was derived in [7]. The structure under study is shown schematically in Fig. 1a. In [7], the finiteness of the metal conductivity was disregarded, and the dependence of the microwave parameters of the system on the distance to the screen was analyzed. For example, it was shown that the dispersion equation for the structure described has the form:

\begin{equation}
\left(1 + 2 \frac{\omega_H}{\omega_M} + 2s \frac{\omega}{\omega_M}\right) \frac{\omega_M}{\omega_M} + \left(\frac{\omega_H - s\omega}{\omega_M}\right)(1 + \tanh(kt)) = e^{-2kd}. \tag{1}
\end{equation}

Here, d is the film thickness, t is the distance to the metal, and s is a parameter characterizing the propagation direction of the surface SW. Figure 1b shows the dispersion characteristics calculated by...
formula (1) at various distances to the metal. It can be seen in the figures that the SW dispersion substantially changes as the conducting screen approaches the film. In particular, the frequency sharply grows at small values of \( k \).

Figure 1. (a) Structure of a screened film, and (b) dispersion characteristics for various distances between the film and the metal.

The dispersion and dissipation parameters of SWs in ferrite-semiconductor structures were calculated in [8] with consideration for the finite value of the conductivity. A dispersion equation for surface SWs propagating in a planar ferrite-semiconductor waveguide was obtained in [8] in terms of the hydrodynamic model for a ferrite and semiconductor in the magnetostatic approximation, without consideration for the exchange interaction. This dispersion equation has the form

\[
e^{-2kd} = \frac{(\mu^+ + k)(\delta \mu^+ - k) \tanh(k,t) + (\mu^+ + k)\sqrt{\delta}}{(\mu^+ - k)(\delta \mu^+ - k) \tanh(k,t) + (\mu^+ - k)\sqrt{\delta}}.
\] (2)

Here, \( \mu^\pm = \mu(\pm \mu_a) \), \( k_a = \delta k^2 \), \( k = k_1 + ik_2 \); \( d \) and \( t \) are the thicknesses of the ferrite and semiconductor layers, respectively; and \( \mu \) and \( \mu_a \) are the diagonal and nondiagonal elements of the ferrite permeability tensor. The value of \( \delta \) determines the specific features of the SW interaction with the semiconductor layer, and \( \delta = f(\omega) \). Thus, the expression obtained in [7] makes it possible to simulate both the dispersion characteristics and the variation of the SW dissipation parameter for different semiconductor wafers. In the case of \( \delta = 1 \), expression (2) becomes the Damon-Eschbach equation [9]. Figure 2a plots the dispersion dependences of surface SWs for various carrier concentrations. It can be seen in the figure that the SW dispersion changes under the action of the carrier concentration in the semiconductor, beginning at the concentration \( N = 10^{15} \) cm\(^{-3} \). With increasing \( N \), the curves shift toward the curve corresponding to the metallized film. It should be noted that, because of the finite value of the conductivity of the semiconductor film, its effect is equivalent to the influence of a metallic layer moved away to a certain distance. This effect can be attributed to the existence of a skin layer in the conducting film.

Figure 2b shows calculated dependences of the loss in the ferrite-semiconductor structure at various carrier concentrations in the semiconductor. It can be seen that, with increasing \( N \), the loss at large SW wave numbers decreases.

It is physically clear that measuring the SW dispersion and dissipation parameters in ferrite-semiconductor structures makes it possible to estimate the parameters of the semiconductor structures, such as conductivity and distance to the doping region. Measurements of the resonance characteristics of a cavity based on the YIG/diamond layered structure will provide information about the free carrier concentration and, consequently, about the emission intensity.
Figure 3 shows schematically the experimental setup making it possible to experimentally study the UV detector. The detector was fabricated from a YIG/diamond layered structure. The YIG film was grown on a gallium-gadolinium garnet (GGG) substrate by liquid-phase epitaxy. The thickness of the YIG film was 6 μm. A film cavity with a plane size of 3×3 mm² was cut from this film. On top of the cavity was attached a 3.5×3.5 mm² single-crystal diamond film. The resulting structure was placed in a dc magnetic field directed tangentially to the plane of the films. The field strength was chosen so that the YIG cavity was magnetized to saturation.

\[
\begin{align*}
(1) & \quad N = 10^{13}, \\
(2) & \quad N = 10^{15}, \text{ and } \\
(3) & \quad N = 10^{17}
\end{align*}
\]

**Figure 2.** Dependences of the microwave parameters of ferrite-semiconductor structures at various carrier concentrations in the semiconductor. (a) Dispersion characteristic and (b) frequency dependence of the loss.

**Figure 3.** Schematic of the setup for studying the UV sensor based on the diamond/YIG structure.

The microstrip antenna was used to excite magnetization oscillations in the layered cavity. The frequency of the resonance modes was determined by the characteristics of the structures from which
the cavity was fabricated. It should be recalled that the carrier concentration in the diamond film will affect the frequency and Q-factor of the resonance peaks.

To evaluate this effect, it is necessary to calculate the resonance frequencies of the YIG/diamond cavity on the assumption that diamond is an insulator. These frequencies will be determined by the SW dispersion in the tangentially magnetized film and by the cavity dimensions (width $w$ and length $l$). The relationship between the frequency and wave number can be found using the dispersion equation of the form $f_{\text{res}} = D(k_{\text{res}})$, where $k_{\text{res}} = \sqrt{(k_{||})^2 + (k_{\perp})^2}$ is the resonance wave number, $k_{||} = \frac{\pi m}{w}$, $k_{\perp} = \frac{\pi n}{w}$ are the longitudinal and transverse wave numbers, and $m$ and $n$ are the numbers determining the distributions of the magnetostatic potential along and across the magnetization direction.

For the cavity described above, $w = 3$ mm and $l = 3$ mm. In the course of the simulation, we calculated the dispersion characteristic of the tangentially magnetized layered structure. The simulation results are presented in Fig. 4a. Choosing the values of $m$ and $n$, we can determine the corresponding resonance frequencies.

$$\text{(a)} \quad \text{(b)}$$

![Figure 4](image)

**Figure 4.** (a) Dispersion characteristic of the SW in a tangentially magnetized YIG film and (b) dependence of the intensity of a reflected wave on the wavelength for the cases of only a mirror (light line) and a mirror with diamond (dark line).

In order to investigate absorption of experimental sample in UV range in the second stage of the study, we measured the optical properties of the single-crystal diamond. Experimental procedure was carried out as follows: initially light in a wide range of wavelengths (200-600 nm) emitted by deuterium lamp was applied to a mirror and power of reflected signal was measured (line 1 in the figure 4b). Then an experimental sample was placed on the mirror. The mirror-sample system was exposed to light and the power of reflected light was measured again (line 2 in the figure 4b). It can be seen that diamond can reduce the reflected signal in nearly the whole range of wavelengths. However, the light line lies above the dark line at 200-300 nm. This can be attributed to the absorption of light via transitions of electrons from the valence band to the conduction band.

The absorption was measured for two samples. Figure 5 shows normalized reflectance plots. These plots were obtained by subtracting from the level corresponding to the reflection from the mirror that corresponding to the reflection from the mirror with diamond. Figure 5a corresponds to the case of diamond with low impurity content. Figure 5b shows a similar dependence for a diamond sample with
high concentration of the nitrogen impurity. The presence of such an impurity resulted in that a yellow tint appeared.

It can be seen from the plots in Fig. 5a that the maximum absorption is observed at a wavelength of 220 nm, which corresponds to the energy gap width of 5.64 eV. This value is in good agreement with reference data, which points to a high purity of the diamond film and to the possibility of using this film as the conducting layer in a UV sensor.

![Figure 5a](image1.png)  ![Figure 5b](image2.png)

**Figure 5.** Normalized reflection level for (a) "pure" diamond sample and (b) impurity diamond sample.

Figure 5b shows the characteristic of the "yellow" impurity diamond. The absorption begins at 450-500 nm. This confirms the assumption that there exists a nitrogen impurity that gives rise to additional impurity sublevels in the energy gap of diamond. Electrons are excited to the conduction band from these additional levels at a lower energy, compared with pure diamond.

Thus, the design of a UV sensor based on a YIG/diamond microwave cavity was presented. The advantages of the suggested design are the following: simplicity of fabrication, fast operation speed, and high sensitivity. Its experimental characteristics will be reported elsewhere.

The work at SPbETU was supported in part by the Russian Foundation for Basic Research, grant of President of Russian Federation for young scientists and PhDs MK-6229.2015.8, and by Ministry of Education and Science of Russian Federation (Project "Goszadanie"). The work at IAP RAS was supported by Act 220 of the Russian Government (Agreement No. 14.B25.31.0021).

**References**

[1] Gwyn C W, Stulen R, Sweeney D and Attwood D 1998 *J. Vac. Sc. & Tech. B.* 16 3142
[2] Kania D R, Landsrass M I, Plano M A, Pan L S, & Han S *Diamond and Related Mater.* 2 1012
[3] Prasad R R 2006 *Diamond Radiation Detectors* (San Leandro: Alameda Applied Science Corporation)
[4] Kagan H *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 546 222
[5] Teraji T, Yoshizaki S, Wada H, Hamada M, Ito T 2004 *Diamond and Related Mater* 13 858
[6] Gurevich A S 1994 *Magnetic Oscillations and Waves* (Moscow: Fizmatlit)
[7] Bongianni W L 1972 *J. Appl. Phys.* 43 2541
[8] Kindyak A S 1994 *Tech. Phys.* 64 99
[9] Damon R W, Eschbach J R 1961 *J. Phys. Chem. Sol.* 19 308