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Investigation of the possibility to use GaAs Hall-effect sensors in active magnetic positioning systems

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Abstract. The paper focuses on the investigation of the possibility to use GaAs Hall-effect sensors (detectors) in active magnetic positioning systems. On the basis of the avalanche S-diode a pulsed magnetic field generator with the pulse front width of 0.3 ns and the current of 10–300 A has been developed. The work studies Hall-effect sensor transient fenomena which transient time is equal to 0.4 ns. The Hall-effect sensor noise in ultra-wide frequency band is estimated. The investigation shows that it is possible to use Hall-effect sensors in active magnetic positioning systems with the operational range of up to 1 m and a few-centimeter spatial resolution.

1. Introduction

In recent times the active magnetic positioning (AMP) systems are developing rapidly. There are designs of current pulse generators on the basis of avalanche S-diodes with switching current of hundreds and thousands amperes [1]. They are used to build high-power generators of pulsed magnetic field with the desired properties giving the opportunity to distinguish signals reflected from the objects under investigation from the Earth magnetic field and noise. One more great advantage of the AMP systems is their capability to determine the direction and the distance to the object of search [2].

As pulsed magnetic fields establish electromagnetic fields whose magnitude is proportional to the rate of change of magnetic flux, it is necessary to create alternating magnetic fields with minimum pulse front widths in magnetic field generators. The current pulse generators give an opportunity to obtain pulses with sub-nanosecond and nanosecond fronts. The Hall-effect sensors (detectors, HESs) are ones of the most promising elements for contemporary small automatic systems and robots. Small dimensions, simplicity of design, wide band of operational frequencies and low price are important advantages of the HESs over other electromagnetic field transducers.

The main disadvantage of HESs restraining their applicability is low sensitivity. To increase the AMP operational range it is necessary to significantly increase the power of magnetic or electromagnetic pulse transmitter.

In order to increase spatial resolution, high-power pulses of sub-nanosecond duration with big duty cycle, spectrum of units and tens GHz and repetition rate of units and tens Hz are used.

Today it is important to investigate the possibility of HES to register pulsed magnetic fields with nanosecond and sub-nanosecond ranges of pulse duration and to operate with microwave signals.

The purposes of the work are the investigation of noise characteristics of HES operating in ultra-wide frequency band, the development of high-power nanosecond alternating pulsed magnetic field generators and the study of HES operational speed at receiving nanosecond pulses of magnetic field.

2. Test samples and measurement technique

The Hall-effect sensors were manufactured from GaAs layers formed on semi-insulating wafer by means of vapor-phase (VPE) and molecular beam (MBE) epitaxy and on the basis of the structures formed with the use of ion implantation doping (IID) methods. Epitaxial vapor-phase and molecular beam structures consisted of 4 layers: n^+-n-n_{bi}-n_i, where n^+ was a contact layer, n was an active layer, n_{bi} was a buffer high-resistance layer and n_i was semi-insulating wafer; ion doped structures had 3 layers: n^+-n-n_i. All of them had submicron dimensions.

The motion equation for charge carriers *e* in isotopic semiconductor with dielectric permittivity ε containing *n* free carriers per unit of volume with effective mass m^* and speed *V* in alternating harmonic fields with frequency ω is shown below:

$$m^* \frac{dV}{dt} + \frac{m^*}{\tau} \cdot \vec{V} = e \cdot \left(\vec{E} + \left[\vec{V} \times \vec{B} \right] \right) \tag{1}$$

The solution of the equation (1), when field is harmonic and $t \gg \tau$,has the following form:

$$E_H = \frac{b}{2} \times \frac{\mu_0 \mu \cdot E_{0y} H_{0z}}{1 + (\omega\tau)^2} \tag{2}$$

where E_H is strength of Hall field, *b* is charge-carriers mobility, μ is relative magnetic permittivity of the material, μ_0 is magnetic constant.

Using this equation it is possible to estimate the change of sensitivity at changing field frequency ω comparing to collision frequency $\omega_0 = 2\pi/\tau$.

From the expression (2) it follows that Hall voltage depends significantly on charge-carrier relaxation time which is defined by sensor material parameters presented in table 1.

Table 1. The parameters of the Hall-effect sensor material

	Material	*R*, kΩ	*n*, cm^{-3}	τ, s
1	GaAs, VPE	0.3	2×10^{16}	8×10^{-10}
2	GaAs, VPE	0.5	1.5×10^{16}	6×10^{-10}
3	GaAs, MBE	0.1	1.1×10^{17}	4×10^{-11}
4	GaAs, IID	0.2	2×10^{17}	6×10^{-11}

The investigation of the Hall-effect sensor operational speed was carried out with the use of the scheme shown in figure 1, where Gen is generator or shaper of pulsed magnetic field.

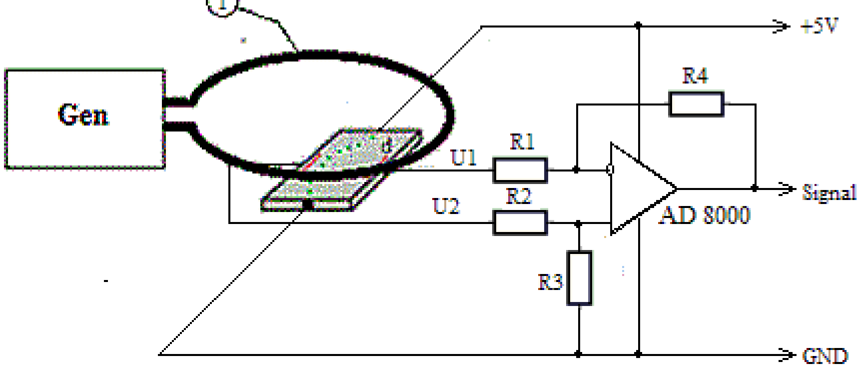

Figure 1. A scheme of generation of pulsed magnetic field.

A circuit diagram of the pulsed magnetic field generator is shown in figure 2.

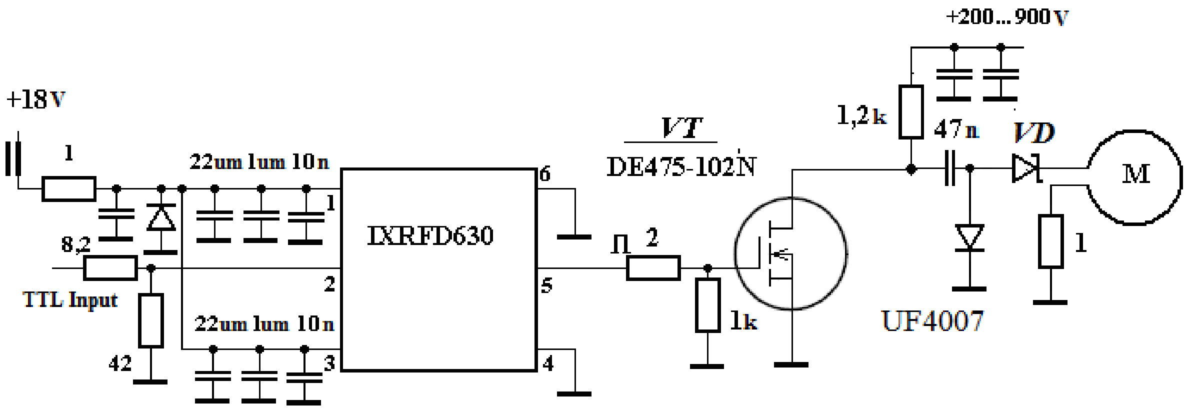

Figure 2. A circuit diagram of the pulsed magnetic field generator.

The dependency of magnetic field on time was defined by registering a shape of the current flowing through the resistor. The measuring of characteristics was conducted by means of LeCroy 600 oscilloscope with a bandwidth of 600 MHz. The direct measuring of magnetic fields in nanosecond widths band was impossible due to lack of corresponding sensors, so the setting time of the magnetic field was assumed to be equal to the setting time of the current flowing through the sending coil.

In order to obtain small rise time, the sender had a form of a copper cylinder with a slot that had height of 30 mm. The diameter of the cylinder was 25 mm and its calculated self-inductance was equal to 1.5 nH (M in figure 2). The current pulse magnitude had a value from 10 to 300 A, the peak induction of the generated magnetic field achieved 0.1 T, an inherent pulse front was about 0.3 ns.

To amplify and match output signal, the Hall-effect sensor was used together with high-speed operational amplifier AD 8000. A Hall-effect sensor connection scheme is shown in figure 3.

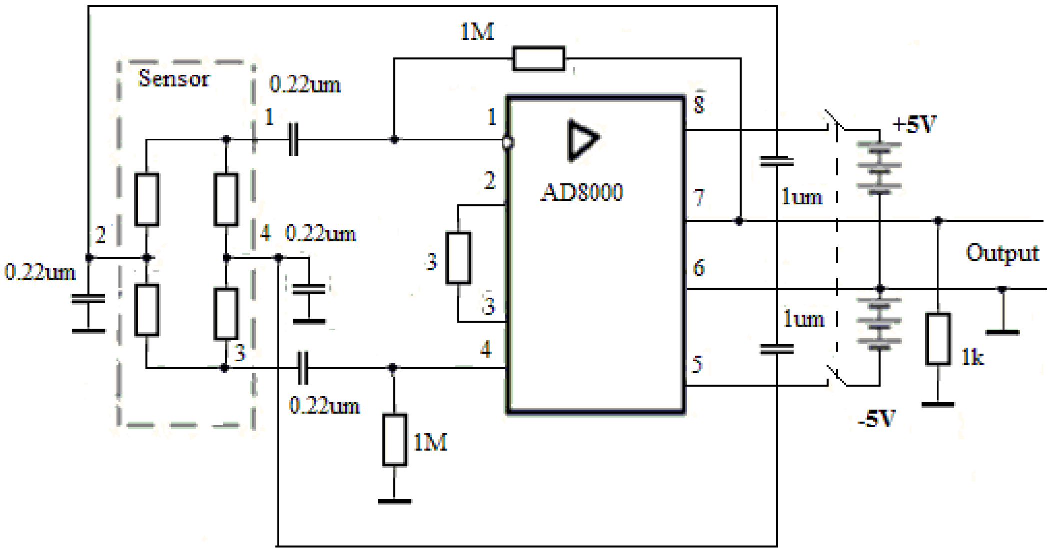

Figure 3. Hall-effect sensor with the amplifier.

3. Experimental results

One of the most important HES characteristics is its threshold sensitivity, i. e. the minimum power P_0 which can be registered by the Hall-effect sensor. This parameter is defined by HES noises [3].

$$P_0 = \frac{U_{nT}^2}{\gamma} \times \frac{\sqrt{4kT \cdot R_H \cdot \Delta f}}{\mu_0 \mu \cdot u \cdot b} \tag{3}$$

where γ is magnetic sensitivity, k is Boltzmann constant, T is absolute temperature, R_H is Hall constant, and Δf is the amplifier bandwidth in hertz.

In order to estimate the noise of the sensor, the Unipan-223 selective nanovoltmeter without preliminary amplification is used. The calculation procedure is presented in [4]. In figure 4 there is the dependence of spectral noise density on frequency at various values of the current flowing through the epitaxial sample, specifically 0.1, 1, and 3 mA. In [4] it is shown that in Hall-effect sensors the main components of internal noise are thermal, shrot (current), and 1/f (flicker) noises. The investigations [2] prove that the main role is played by thermal noise. In the case of thermal noise the mean square of noise voltage is defined by the Nyquist formula [3]:

$$U^2 = 4kTR\Delta f \tag{4}$$

where R is an active resistance of the noise source under measurement, Δf is a frequency band of the noise-measuring device. The estimation of thermal noise according to the expression (4) gives the value U^2=1.6×10^{-17}×Δf [V^2×s].

Figure 4 shows the obtained dependencies of spectral noise density on frequency for epitaxial sample at the following current values: 0.1, 1, and 3 mA.

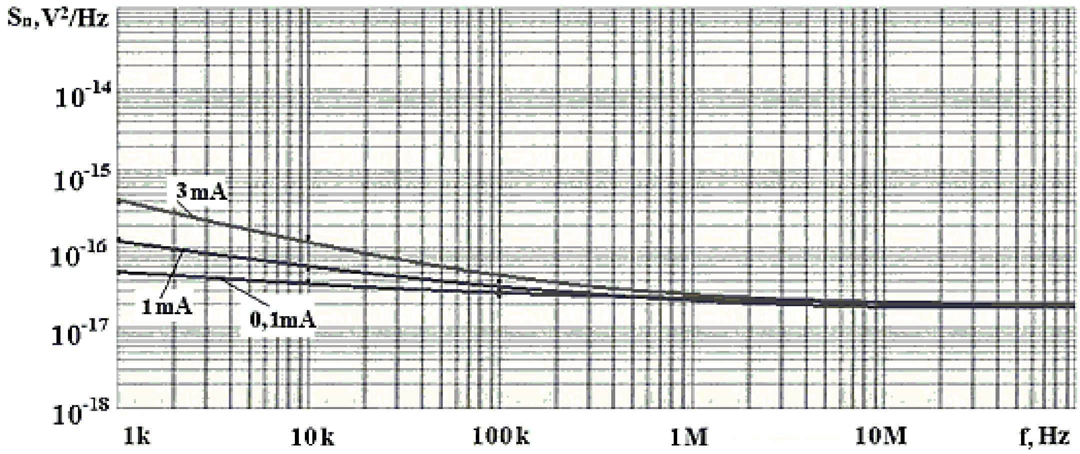

Figure 4. The dependences of spectral noise density on frequency at various values of the current flowing through the sample.

It is seen from the figure that as the current flowing through the sample increases the noise voltage value increases too. The curves obtained at I=0.1, 1, and 3 mA are qualitatively identical. With the frequency growth the dependences are smoothed and don't depend on current in the range under investigation. The spectral noise density S_n=2×10^{-17} V^2/Hz. Being aware of thermal noise value, it is possible to estimate a threshold inductance of the magnetic field. At higher frequency 100 MHz the width of noise grass is 1 mV.

The experimental results of the Hall-effect sensor operational speed investigation with the use of the assembly with pulsed magnetic field generator (figure 1) are shown in figure 5.

Using the oscillograms it is possible to calculate transient time for Hall-effect sensor with the amplifier. The input signal front t_{isf} =1.47 s; the output signal front t_{osf}=1.52 s. Then,

$$t_{\text{int}} = \sqrt{t_{osf}^2 - t_{isf}^2} \approx 0.4ns$$

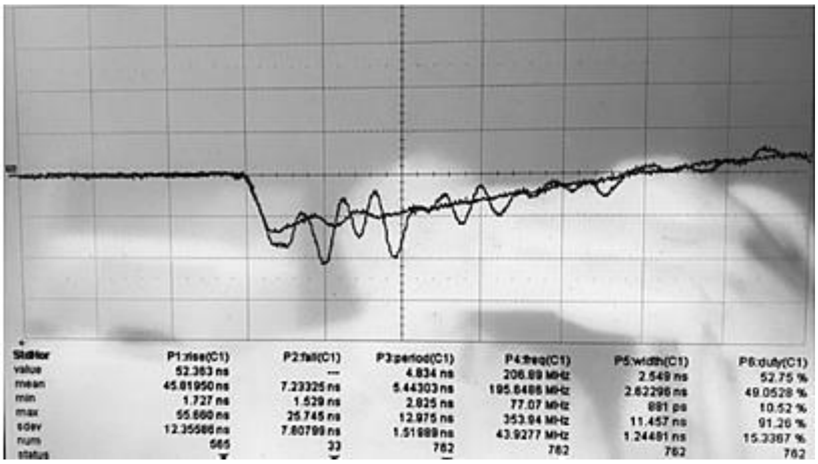

Figure 5. The oscillograms of the current flowing through the coil (the upper line) at scale of 10 V/div for vertical axis and 10 ns/div for horizontal axis and the HES operational amplifier output voltage (the lower line with oscillations) at scale of 2 V/div for vertical axis and 10 ns/div for horizontal axis.

The calculated value of the upper frequency is equal to 1 GHz which corresponds to the bandwidth of the amplifier built at the basis of the operational amplifier.

At the obtained peak value of the generated magnetic field induction equal to 0.1 T and at threshold noise value equal to 3 mV the distance in which the signal can be detected is equal approximately to 1 m.

4. Results of the work and conclusions

The carried out investigation leads to the conclusions stated below.

- Semiconductor materials with high carrier density have lower relaxation time, yet their sensitivity is lower, so they should be used in microwave applications.
- It is shown that there is a possibility to generate pulsed magnetic field with the induction of up to 0.1 T and the pulse front width of 300 ps using commutators based on the avalanche S-diodes.
- The Hall-effect sensor sensitivity at pulsed magnetic field receive and operation in ultra-wide frequency band has been estimated, spectral noise density is equal to 2×10^{-17} V^2/Hz. At Hell-effect sensor sensitivity of 1.6–1.8 V/T, the subnanosecond magnetic field detection threshold is equal to 2 mT.
- It is shown that there is a possibility in principle to use Hall-effect sensors in AMP systems with operational range of up to 1 m and a few-centimeter spacial resolution.

It is planned in future to develop generators of complex subnanosecond magnetic fields with subsequent signal accumulation, as well as to increase pulsed power of the transmitter in order to widen the operational range of the active magnetic locator.

References

[1] Avdochenko B I, Prudaev I A, Tolbanov O P, Chumerin P Y and Yurchenko V I 2016 A solid-stste sub-nanosecond microwave switch *Russian Physics Journal* **59 8** 1187-91

[2] Avdochenko B I and Karlova G F 2018 Phased Array Antenna Element for Active Magnetic Positioning System based on Semiconductor Hall - Effect Sensors *14th international scientific technical conference on actual problems of electronic instrument engineering* (APEIE-2018)-44894

[3] Van der Ziel A 1973 Noise New York Peentici Mall 418

[4] Karlova G F and Gradoboev A V 2013 Radiation characteristics of hall-sensor on the base of gallium arsenide 2013 International Siberian Conference on Control and Communications, SIBCON 2013*: Proc. IEEE Computer Society* ISBN 9781479910601