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O.A. Klimenko, Y.A. Mityagin, H. Videlier, F. Teppe, N.V. Dyakonova, et al.. Terahertz response of InGaAs field effect transistors in quantizing magnetic fields. *Applied Physics Letters*, 2010, 97 (2), pp.022111. 10.1063/1.3462072 . hal-00548568

**HAL Id: hal-00548568**

**<https://hal.science/hal-00548568>**

Submitted on 31 May 2022

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Cite as: Appl. Phys. Lett. **97**, 022111 (2010); <https://doi.org/10.1063/1.3462072>  
Submitted: 31 May 2010 • Accepted: 14 June 2010 • Published Online: 16 July 2010

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## Terahertz response of InGaAs field effect transistors in quantizing magnetic fields

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(Received 31 May 2010; accepted 14 June 2010; published online 16 July 2010)

Terahertz (THz) detection by plasma wave mechanism in InGaAs field effect transistors is studied in high/quantizing magnetic fields regime. The correlation between the photovoltaic response and magnetoresistance is revealed. It allows explaining the dominant physical mechanism responsible for strong oscillations observed in the transistor THz photoresponse. The results indicate also a serious discrepancy between experimental data and existing theoretical model. © 2010 American Institute of Physics. [doi:10.1063/1.3462072]

Field effect transistors (FETs) were recently shown to be efficient terahertz (THz) and sub-THz detectors.<sup>1,2</sup> Their advantages consist in a very high operation speed and small dimensions, which allow applications for THz imaging.

The mechanism of detection is related to rectification of the THz radiation by nonlinear properties of the two-dimensional plasma confined in the transistor channel.<sup>1,2</sup>

Studies of FETs THz response in magnetic fields are of considerable interest, since the magnetic field strongly affects the carrier transport properties in the transistor channel. Therefore they may provide supplementary information for better understanding of detection mechanism.

Recent experimental studies have shown that application of magnetic field leads to drastic increase in the FET's photoresponse. The photoresponse revealed also oscillatory structures similar to well known Shubnikov–de Haas (SdH) oscillations.<sup>3,4</sup> The SdH like oscillations observed in the photoresponse were however never compared to real SdH oscillations usually observed in magnetoresistance of the transistor channel.

Also, a comparison of the first experimental results with the existing theory<sup>5</sup> demonstrated that the theory can give only a qualitative explanation of the effect. A quantitative description of the observed oscillating photoresponse appeared to be difficult.

In this work, we performed a comparative study of FET's photoresponse and magnetoresistance oscillations in the same FETs to reveal the relationship between SdH and photoresponse oscillations. The main motivation was to put some more light on the physical mechanism of FET photo-detection in quantizing magnetic fields by comparing these two effects and interpreting them in the frame of existing theoretical models.

The measurements were performed on InGaAs/InAlAs HEMTs grown on InP substrate. The gate length, the gate width, and the channel length were 0.8  $\mu\text{m}$ , 25  $\mu\text{m}$ , and 2.6  $\mu\text{m}$ , respectively. The experiments were carried out at temperature 7 K and magnetic fields up to 15 T. The incident THz radiation of 0.938 THz was provided by a backward wave oscillator (BWO) source. This frequency was selected

to separate in magnetic field scale the cyclotron resonance (CR) and SdH effects.

In Fig. 1 we show the carrier density and the mobility versus the gate voltage determined from magnetoresistance measurements. The mobility was measured in two following ways: from parabolic magnetoresistance behavior in low magnetic fields and from the channel conductivity.

The photoresponse source-drain voltage was measured as a function of magnetic field using a standard lock-in technique.<sup>3</sup> Both the photoresponse and the magnetoresistance were measured simultaneously in a wide range of gate voltages. The results in a full range of carrier densities from open to close states of the transistor were obtained.

The measured photoresponse dependences as functions of magnetic field,  $B$ , revealed a pronounced oscillating behavior (Fig. 2) periodic with  $1/B$ . The amplitude of the detected signal in magnetic field was found to be much higher than at  $B=0$ . Not only the amplitude of the photoresponse signal but also its polarity oscillated with the magnetic field.

The measured magnetoresistance also revealed oscillations periodic in  $1/B$ , correlated with those of the photoresponse curves (Fig. 2). The periods of the both types of os-

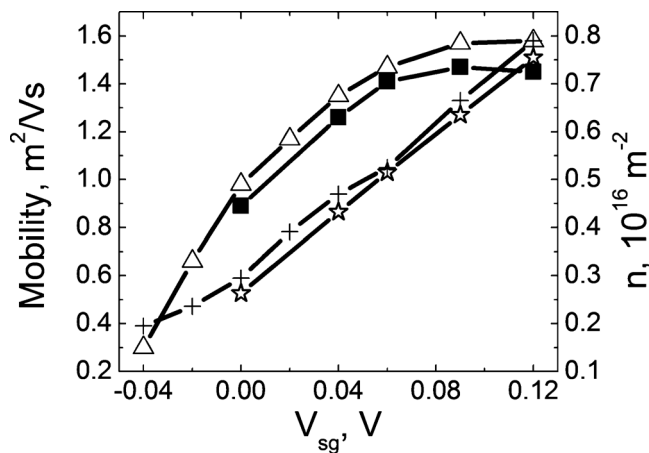


FIG. 1. Measured mobility (triangles and squares) and electron concentration (stars and crosses) as functions of the gate voltage for InGaAs/InAlAs HEMTs. Concentration was determined both from period of SdH oscillations (stars) and from period of photoresponse oscillations (crosses).

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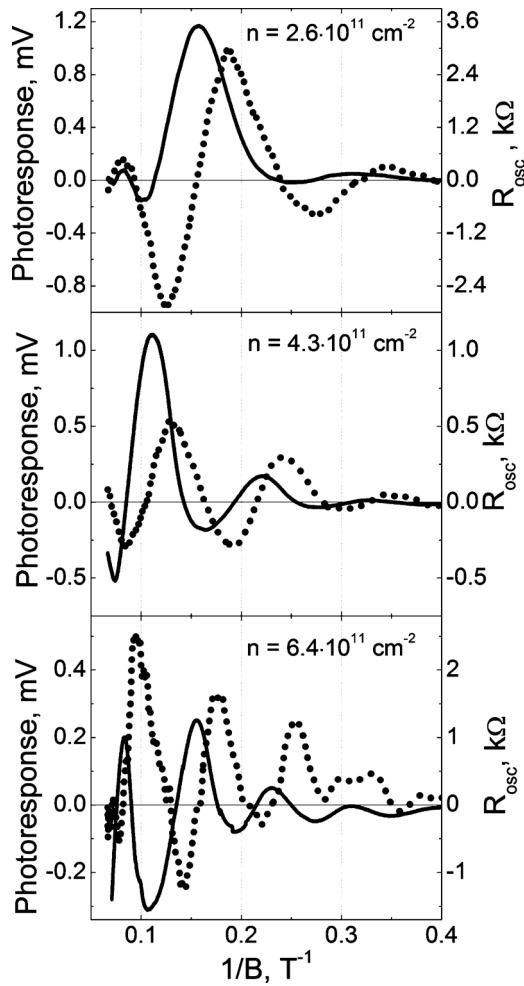


FIG. 2. The photovoltaic response (solid curves) and the oscillating part of the magnetoresistance  $R_{osc}$  (dotted curves) of InGaAs HEMT vs inversed magnetic field, measured for different electron concentration in the transistor channel.

cillations were the same and depended on the gate voltage in the same manner. This can be seen in Fig. 2. Also the carrier densities determined from SdH and from photoresponse oscillation periods were the same—see Fig. 1.

The strong correlation between two effects may be considered as a direct experimental confirmation that the observed photoresponse is related to the electron plasma in the gated part of the transistor channel.

The most remarkable effect is  $\pi/2$  phase shift between photoresponse and magnetoresistance oscillations (Fig. 2). Summarizing experimental observations one can say that photoresponse and SdH oscillations have the same periodicity but are shifted by  $\pi/2$ . Both effects (the periodicity and the phase shift) are predicted by Lifshits–Dyakonov theory.<sup>5</sup> Really, according to Ref. 5 the magnetic field dependence of the photoresponse can be expressed by

$$\Delta U = \frac{1}{4} \frac{U_a^2}{U_0} \left[ f(\beta) - \frac{d\gamma n}{dn \gamma} g(\beta) \right]. \quad (1)$$

Here  $\Delta U$  is the photoresponse signal,  $U_a$  is the amplitude of the ac modulation of the gate-to-source voltage by the incoming radiation,  $U_0$  is the static value of the gate-to-channel voltage,  $n$  is the electron concentration in the channel,  $\beta = \omega_c/\omega$ ,  $f(\beta)$ , and  $g(\beta)$  are slowly changing functions of magnetic field as follows:

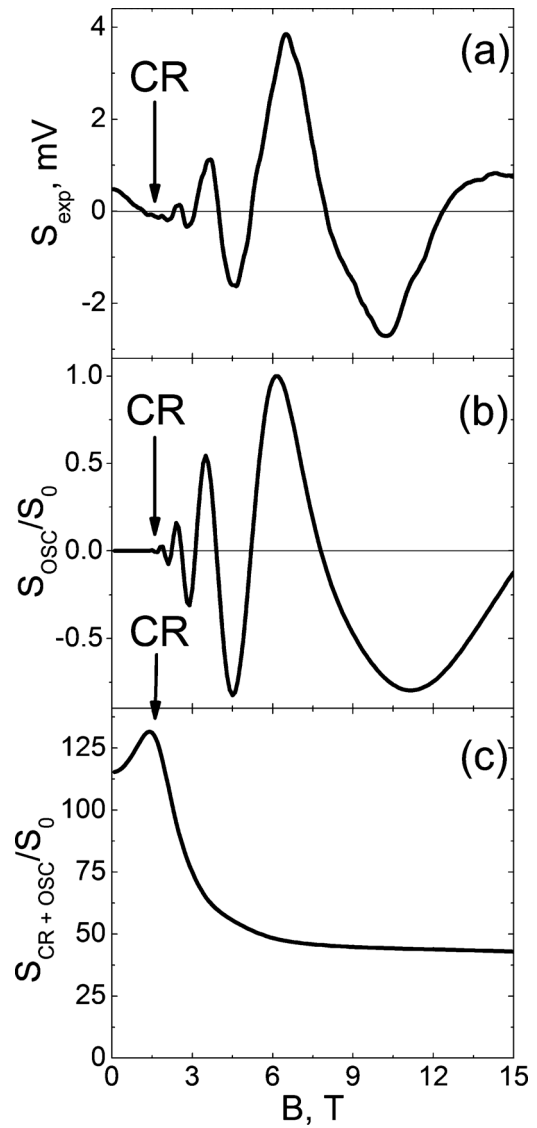


FIG. 3. (a) Experimental photoresponse vs magnetic field for electron concentration  $n=3.5 \times 10^{11} \text{ cm}^{-2}$ ; (b) calculated photoresponse  $S_{osc}$  using only the second term in formula (1); and (c) photoresponse calculated by total formula (1). Curves in (b) and (c) are normalized on  $S_0$ —value of  $S_{osc}$  at  $B=6.2 \text{ T}$ .

$$f(\beta) = 1 + \frac{1+F}{\sqrt{\alpha^2 + F^2}}$$

$$\text{and } g(\beta) = \frac{1+F}{2} \left( 1 + \frac{1}{\sqrt{\alpha^2 + F^2}} \right),$$

where

$$F = \frac{1 + \alpha^2 - \beta^2}{1 + \alpha^2 + \beta^2}, \quad \alpha = (\omega\tau)^{-1}.$$

The parameter  $\gamma$  is an oscillating function of the electron concentration and magnetic field, which results in the SdH oscillations. The first term in Eq. (1) describes a contribution of the CR. The second term responsible for the oscillations is proportional to  $d\gamma/dn$ , or, as it can be easily shown, to  $d\gamma/dB$ , thus resulting in  $\pi/2$  phase shift, which we observe in experiment. This gives a strong evidence in favor of the detection mechanism proposed in Ref. 5.

To make a direct comparison of the theory with experiment we calculated the photoresponse given by Eq. (1) for actual parameters of the investigated transistor.

The results are shown in Fig. 3. From comparing Fig. 3(a) with Fig. 3(b) one can see that retaining only the second term in Eq. (1) allows to achieve a good agreement with the experiment [Figs. 3(a) and 3(b)].

We would like to mention that also in previous work<sup>4</sup> only the second term of Eq. (1) was used for interpretation of the photoresponse.

But if both terms are used in calculations, theoretical predictions strikingly differ from the experiment [see Fig. 3(c)]. It turns out that the calculated contribution of the first (CR) term in Eq. (1) is two orders of magnitude higher than that of the second term, responsible for oscillations. In the experiment, the opposite situation is observed—the oscillating part of the photoresponse dominates, while the CR contribution is not visible.

The analysis of Eq. (1) shows a strong dependence of the second term function  $g(\beta)$  on the electron mobility. Therefore we checked if the discrepancy may be reduced by variation in the mobility value. However, the variation in the mobility value in simulations does not allow to considerably decrease the amplitude of CR term and to achieve the photoresponse curve periodically changing polarity of the signal, as it was experimentally observed.

In conclusion, the comparative study of THz photoresponse and magnetoresistance in quantizing magnetic field allowed to establish a correlation between two effects and to confirm experimentally that the observed photoresponse is due to the rectification mechanism as described by the oscil-

latory part of theoretical formula. A comparison of existing experimental results with theory showed that theory gives a satisfactory explanation of the detection mechanism only in the case when CR term is neglected. Otherwise a serious discrepancy between experimental results and theory appears.

The reason why one should neglect the CR term to avoid the discrepancies between the theory and our experimental data is not clear and indicates that further improvement/development of the theoretical description of the effect is necessary.

We thank M. I. Dyakonov and M. B. Lifshits for helpful discussions. The work was partly supported by Russian Foundation for Basic Research (Project Nos. 08-02-92505-NCNIL\_a and 09-02-00671). We also acknowledge ANR-JST French—Japanese collaborative project “WITH” and GDR-I project Sources and Detectors of Terahertz Radiation.

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