Comment on “Theory of microwave-induced zero-resistance states in two-dimensional electron systems” and on “Microwave-induced zero-resistance states and second-harmonic generation in an ultraclean two-dimensional electron gas”

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Comment on "Theory of microwave-induced zero-resistance states in two-dimensional electron systems" and on "Microwave-induced zero-resistance states and second-harmonic generation in an ultraclean two-dimensional electron gas"

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Recent papers by S. A. Mikhailov [Phys. Rev. B **83**, 155303 (2011) and Phys. Rev. B **89**, 045410 (2014)] claim to explain "all experimental facts" pertinent to microwave-induced resistance oscillations and zero-resistance states in terms of "the ponderomotive force theory". This Comment shows that the analysis of the results obtained in the above mentioned papers, in fact, leads to opposite conclusions, i.e., that they cannot explain even the most basic experimental facts.

The abstract of Ref. 1 states: *"The phenomena of microwave-induced zero-resistance states (MIZRS) and microwave-induced resistance oscillations (MIRO) were discovered in ultraclean two-dimensional electron systems in 2001−2003 and have attracted great interest from researchers. In spite of numerous theoretical efforts, the true origin of these effects remains unknown so far. We show that the MIRO-ZRS phenomena are naturally explained by the influence of the ponderomotive forces which arise in the near-contact regions of two-dimensional electron gas under the action of microwaves. The proposed analytical theory is in agreement with all experimental facts accumulated so far and provides a simple and self-evident explanation of the microwave frequency, polarization, magnetic field, mobility, power, and temperature dependencies of the observed effects."*

Ref. 2 reiterates the above claims: *"A comprehensive theory of these phenomena was developed in 2011: It was shown that all experimentally observed dependencies can be naturally explained by the influence of the ponderomotive forces which arise in the near-contact regions of the two-dimensional electron gas under the action of microwaves. ... A part of this paper is devoted to a further development of the ponderomotive-force theory: we show how it explains different experimental details, including those which were not known in 2011."*

The purpose of this Comment is to inform the reader that the results of Refs. 1,2 fail cannot be used to explain even the most basic experimental facts of MIRO/MIZRS.

Summary of main results of Ref. 1 – Equation (13) of Ref. 1, states that [3]

$$R_{xx} = R_{xx}^{b} \cdot \mathcal{N}\,, \tag{1}$$

where R_{xx} is the the "measured resistance", R_{xx}^{b} is the bulk resistance [4], and $\mathcal{N}$ is the density factor, defined as the ratio of the electron density in the near-contact region to that in the bulk. Ref. 1 then argues that the radiation-induced changes in the "measured resistance" originate primarily from the radiation-induced changes in $\mathcal{N}$. More specifically, $N > 1$ and $N < 1$ correspond to the MIRO maxima and minima, respectively.

For simplicity, we limit the discussion to the fundamental MIRO/MIZRS occurring near the cyclotron resonance, where the density factor can be expressed as [5]

$$\mathcal{N} = t \ln\left\{(1 + \exp[(1 - \mathcal{P}_c \mathcal{B}_1)/t]\right\}\,, \tag{2}$$

where $t = k_B T/E_F$, k_B is the Boltzmann constant, T is the temperature, E_F is the Fermi energy of the 2D gas, $\mathcal{P}_c$ is the dimensionless measure of the microwave power, and

$$\mathcal{B}_1 \approx \frac{\epsilon^2(\epsilon-1)}{2[(\epsilon-1)^2 + \Gamma^2\epsilon^2]}\,. \tag{3}$$

Here, $\epsilon = \omega/\omega_{\rm c}$, $\omega = 2\pi f$ is the microwave frequency, $\omega_{\rm c} = eB/m^\star$ is the cyclotron frequency of an electron with the effective mass $m^\star$, and $\Gamma \equiv (\omega\tau)^{-1} \ll 1$, where τ is the transport scattering time.

The extrema of $\mathcal{B}_1$ occur at

$$\epsilon^{\pm} \approx 1 \mp \Gamma\,, \tag{4}$$

and are given by $\mathcal{B}_1^{\pm} = \mp(4\Gamma)^{-1}$. As a result, at the MIRO maximum (+) and minimum (−), the density factor takes the form:

$$\mathcal{N}_{\pm} = t \ln\left\{(1 + \exp[(1 \pm p)/t]\right\}\,,\ p \equiv \mathcal{P}_c/4\Gamma\,. \tag{5}$$

Since $t \ll 1$, the MIRO maximum is described by

$$\mathcal{N}_{+} \approx 1 + p\,, \tag{6}$$

while for the MIRO minimum one finds

$$\mathcal{N}_{-} \approx \begin{cases} 1 - p\,, & p < 1 - t \quad \text{(7a)} \\ t \ln 2\,, & p = 1 \quad \text{(7b)} \\ t \exp[(1-p)/t]\,, & p > 1 + t \quad \text{(7c)} \end{cases}$$

In what follows, these results are examined in relation to established experimental facts.

Temperature dependence of MIRO/ZRS – Experimentally, it is well known that MIRO become weaker with increasing temperature [6–14]. For example, Ref. 12 have shown that in their experiment the temperature dependence originated from electron-electron interactions modifying the single particle lifetime [15, 16]. The same mechanism was later confirmed in studies of the temperature dependence of other related phenomena [17–20].

While Section I.E.2 in Ref. 1 starts with *"How do the MIRO and MIZRS depend on the microwave power and temperature?"*, it contains no discussion of the MIRO temperature dependence. The obvious reason for the lack of such a discussion is that Ref. 1, in fact, predicts *temperature-independent* MIRO, cf. Eqs. (6),(7a), contradicting all experiments performed to date [6–14].

Microwave-induced zero-resistance states evolve from the MIRO minima with decreasing temperature [7, 8, 11, 21]. Since Eq. (7a) is T-independent, it is already clear that Ref. 1 cannot possibly explain such evolution. Nevertheless, Ref. 1 claims that it is the Eq. (7c) which accounts for the experimentally observed MIZRS temperature dependence. Here, it is instructive to recall that in experiments which have reported activation behavior $R_{xx} \sim \exp(-\Delta/T)$, the temperature range is limited to $t \approx 0.007 - 0.02$. Over this range of t, R_{xx} increases by about two orders of magnitude, implying that $\mathcal{N}_-$ varies from $\sim 10^{-2}$ and 1. At the lowest T, Eq. (7b) gives $\mathcal{N}_- \approx t\ln 2 \approx 0.005$, suggesting that the regime of Eq. (7c), claimed to explain the activation behavior of MIZRS, lies outside the regime of experiments [22].

The "phase" of MIRO – The "phase" of the k_{th} MIRO maximum, occurring at $\epsilon = \epsilon_{k+}$, is defined as $\delta_k = k - \epsilon_{k+}$. Experimentally, δ_k varies between $\delta_1 \approx 0.1$ and $\delta_{k\geq 4} \approx 0.25$ [9, 10, 23–25]. Using Eq. (4) and parameters from Ref. 25, $\mu \approx 10^7$ cm^2/Vs, $f = 150$ GHz, one finds $\delta_1 = \Gamma \approx 0.003$, much lower than $\delta_1 \approx 0.1$ observed Ref. 25. This result also implies that the commonly observed value of $\delta_k \approx 0.25$ should occur only at $k \gtrsim 80$, while experiments show $k \lesssim 3$. Ref. 2 overcomes this issue by using a much larger value of $\Gamma = 0.05$ (for $f = 150$ GHz, this translates to $\mu \approx 6 \times 10^5$ cm^2/Vs), which allows δ_k to approach 1/4 at $k = 5$. However, even with such an inflated value of Γ, Eq. (4) still yields δ_1 which is two times lower than ever reported.

Power dependence of MIRO – Experimentally, it is well known that the MIRO amplitude often exhibits sublinear dependence on the microwave power [11, 26–29]. Moreover, Ref. 30 has demonstrated a clear crossover from a linear to a square-root dependence with increasing power, which is accompanied by a considerable reduction of the phase. In contrast, Refs. 1,2, predict only linear power dependence of the MIRO amplitude, cf. Eqs. (6),(7a), and no power dependence of the phase, cf. Eq. (4).

Dependence on in-plane magnetic field – It is known that MIRO/MIZRS can be suppressed by an in-plane magnetic field $B_\parallel$ [31–33]. In particular, it was demonstrated [33] that the suppression of the MIRO amplitude can be explained by a $B_\parallel$-induced correction to the quantum scattering rate, $\delta(1/\tau_q) = (1/\tau_q^0)(B_\parallel/B_0)^2$, where τ_q^0 is the quantum lifetime at $B_\parallel = 0$ and $B_0 \approx 0.6$ T. The same behavior was observed in experiments on nonlinear transport without microwave radiation [34].

Ref. 1 claims that *"the suppression of MIZRS by the parallel magnetic fields $B_\parallel \sim 1$ T seems to be completely unbelievable if to think about the influence of $B_\parallel$ on the properties of the 2DEG"*. The claim of Ref. 1 is that the suppression occurs due to the cyclotron resonance of free electrons in three-dimensional metallic contacts. At $f =$ 120 GHz, used in Ref. 31, such cyclotron resonance would occur at $B \approx 4.3$ T. However, the suppression of the MIRO amplitude was observed at total B, which is at least one order of magnitude smaller [31–33].

Dependence on dc electric field – The evidence that MIRO is a bulk phenomenon came from several experiments in which the 2D gas was subject not only to microwave radiation but also to dc electric fields [35–40]. These experiments have demonstrated that the electron transitions are a combination of backscattering off disorder and absorption/emission of microwave quanta. As discussed numerous times [35–46], the observation of electron backscattering relies on the uniformity of the electric field within the *bulk* of the sample. Resonant mixing of MIRO and magneto-inter-subband resistance oscillations [47–50] further proves that MIRO is a bulk phenomenon. It is obvious that Refs. 1,2 cannot account for any of these experimental observations.

Dependence on magnetic field – It is well established that the MIRO amplitude exhibits exponential dependence on the magnetic field, decaying as $B^{-1}\exp(-B_0/B)$ [6, 9, 10, 12, 23, 33, 51], where B_0 is a sample-dependent constant. In contrast to microscopic MIRO theories [46], which link B_0 to the quantum scattering rate, $B_0 = 2\pi m^\star/e\tau_q$, Ref. 1 postulates "that the electron scattering *is not important in the discussed phenomena at all*" while providing no alternative explanation for the observed exponential dependence .

Summary – In summary, the proposals outlined in Refs. 1,2 do not explain major experimental facts of MIRO/MIZRS, in contrast to their claims.

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[2] S. A. Mikhailov, Phys. Rev. B **89**, 045410 (2014).
[3] This Comment does not address the validity of Eq. (13) postulated in Ref. 1.
[4] In Ref. 1 R_{xx}, R_{xx}^b are (incorrectly) termed photoresistances.

[5] For convenience, we redefine $\mathcal{P}_c$ to include $\mathcal{T}_1$ which, typically, is of the order of unity (See Fig. 9(a) in Ref. 1).
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