Random Flips of Electric Field in Microwave-Induced States with Spontaneously Broken Symmetry

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(Received 8 December 2014; published 1 May 2015)

In a two-dimensional electron system subject to microwaves and a magnetic field, photovoltages emerge. They can be separated into two components originating from built-in electric fields and electric field domains arising from spontaneous symmetry breaking. The latter occurs in the zero resistance regime only and manifests itself in pulsed behavior, synchronous across the sample. The pulses show sign reversal. This implies a flip of the field in each domain, consistent with the existence of two equally probable electric field domain configurations due to the spontaneous symmetry breaking.

DOI: 10.1103/PhysRevLett.114.176808 PACS numbers: 73.22.Gk, 73.50.-h

The appearance of domains in solids, for example, in ferromagnets and ferroelectrics, is usually the result of spontaneous symmetry breaking. In the absence of an external field, opposite polarizations or, more generally, opposite orientations of the order parameter in a domain are equally probable. Reversal of polarization occurs only when varying some external parameter or field. Here, we report a random complete reversal of the electric field with time in a system composed of domains with opposite field orientations. This, hitherto unreported, observation emerges in the context of a two-dimensional electron system (2DES) exposed to microwaves and a weak perpendicular magnetic field B.

Microwave irradiation of a 2DES elicits a surprisingly abundant set of physical phenomena, which have been reviewed recently in Ref [1]. The most prominent effect is, no doubt, the appearance of zero resistance states in a GaAs based 2DES [2–5] and in 2D electron systems on a Helium surface [6]. When ramping B, the microwaves induce oscillations of the magnetoresistance [7,8]. They are periodic in the inverse of B and reflect a commensurability between the microwave photon and the cyclotron energy: $\hbar 2\pi f/\hbar\omega_c = n$. Here, $n = 1, 2, \ldots, \omega_c$ is the cyclotron frequency and f the microwave frequency. In high quality samples, the oscillation minima for small n culminate in B-field regions where the dissipative resistivity (and conductivity) tends to zero.

Theory has argued that the microwave radiation may cause the dissipative conductivity to turn negative, and then, the system is no longer stable. It cannot support zero current everywhere nor a homogeneous current flow across. The zero magnetoresistance is a manifestation of spontaneous symmetry breaking and the formation of a stable pattern of current domains even in the absence of net current flow through the sample [9–13]. Domain pairs support identical current densities but with opposite current directions in the domains [9–12]. Accordingly, the Hall electric field in these domains is pointing in opposite directions. By introducing contacts located in the bulk of the sample rather than along its perimeter, it is possible to track, in a discrete manner, the current and Hall voltage distribution across the sample and possibly find evidence for a pattern of domains with opposing Hall electric fields in the zero resistance regime. Unequivocal and direct experimental confirmation of this theoretical model has been lacking, however. The relative weight of the two types of domains is controlled by the net current flow through the sample. In the absence of an externally imposed current, these areas are equal. Large domains on the scale of the sample size are anticipated in order to minimize the energy cost for domain wall formation. In a sample without disorder, domain patterns with the same geometry but opposite orientations of the spontaneous electric field are equally probable configurations. This turns up in a Lyapunov functional, used in the theory, to describe the system stability [14], as two equal minima of the functional for opposite directions of the electric field [11]. A long-range built-in electric field may result in a different depth of the minima, so that one configuration is preferred. The details of the domain configurations with opposite field orientations may also be somewhat affected by disorder with a length scale much less than the typical domain size [10]. Here, we report pulsed behavior of photovoltages induced by continuous wave microwave radiation across sample contacts in the zero resistance regime. The observed switching in the photovoltage is shown to be fully compatible with the assumption that the system alternates erratically between two quasistable configurations with an identical domain pattern, but the electric field in each domain is simply completely reversed upon each switching event. This lends strong credence to the stability model based on a Lyapunov functional with nearly equal minima for opposite directions of the electric field.

Investigations have been performed on four samples from two different GaAs/AlGaAs heterostructures. We present data measured on one sample from each wafer, hereafter referred to as S1 and S2. The electron densities and mobilities are equal to $n_{S1} = 2.6 \times 10^{11}$ cm^{-2}, $n_{S2} = 2.9 \times 10^{11}$ cm^{-2}, $\mu_{S1} = 6 \times 10^{6}$ cm^2/V s, and $\mu_{S2} = 17 \times 10^{6}$ cm^2/V s. All samples are fabricated in a Hall bar shape with 17 contacts. Eight contacts are located along the perimeter. The remaining 9 contacts are placed inside the Hall bar as shown in the inset to Fig. 1(a). Out of the 17 contacts, 15 are arranged in a regular matrix consisting of three columns and five rows. The columns are denoted by capital letters A, B, C, while the rows are referred to with numbers. The source (S) and drain (D) contacts are positioned at the ends. The Hall bar length and width are 2.8 and 0.6 mm, respectively. The internal contacts are square shaped with a side length of 60 μm. The distance between the columns is 400 μm, while the rows of internal contacts are 150 μm apart. The samples are mounted at the center of a rectangular waveguide with a cross section of 6.5×13.0 mm^2 (WG19). Photovoltages generated by the continuous wave microwave radiation and measured across an internal contact and some contact at the perimeter are amplified with a low-noise voltage preamplifier with the upper frequency cutoff set at 10 kHz. Up to four time-dependent signals from different internal contacts can be recorded simultaneously with a digital oscilloscope (Infiniium 54854A DSO). Oscilloscope traces with total lengths between 0.2 and 5 s are measured. Each of these traces consists of approximately 2×10^5 points per channel.

Examples of recorded photovoltages are displayed in Fig. 1. In Fig. 1(a), the solid and dashed lines illustrate the behavior on samples S1 and S2, respectively, in a microwave power regime where no time dependent events in the photovoltage are observed. The photovoltage signal is available across the entire magnetic field range and oscillates relative to the zero level in antiphase with the magnetoresistance (see Ref. [15] and also Refs. [16,17]), so that maxima of the photovoltage coincide with magnetoresistance minima. Upon increasing the power, an additional time dependent contribution to the photovoltage enters the scene while the corresponding magnetoresistance minimum tends to zero. Typical time dependent traces at different B are plotted in Fig. 1(b). They were measured on sample S1. An erratic switching between two quasistable voltage levels is apparent. This switching is not available for all values of the magnetic field, but only at the primary photovoltage peak near 0.095 T in Fig. 1(a) (solid line). For an in-depth analysis of such time-dependent traces, several quantities characterizing the pulse amplitudes are defined and illustrated in Fig. 1(b). The average values of the upper and lower

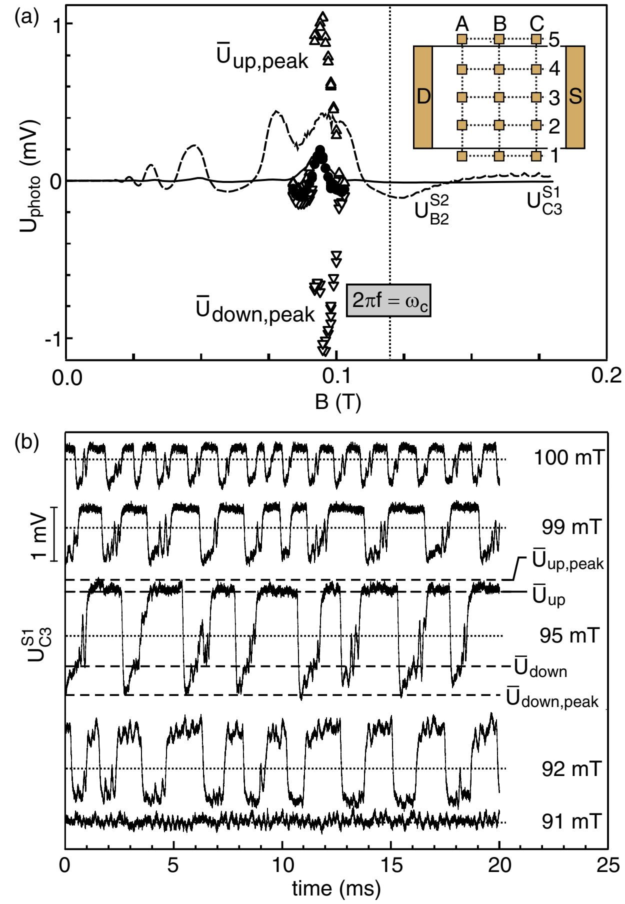

FIG. 1 (color online). (a) Magnetic field dependencies of the dc intrinsic photovoltage (solid line—contact $C3$ of sample S1, dashed line—contact $B2$ of sample S2) measured at a microwave power $P = -15$ dBm. Pulse amplitudes (triangles) and the average of the pulsed photovoltage (circles) as defined in the text and measured at $P = -6$ dBm are also shown. The data were obtained at microwave frequency $f = 50$ GHz and bath temperature of 1.5 K. The vertical line marks where the cyclotron energy matches the microwave photon energy: $2\pi f = \omega_c$. The cyclotron energy was calculated based on the commonly used value of the effective mass $m^* = 0.067 m_e$. The inset schematically shows the sample geometry and the labeling of the contacts. (b) Several fragments of the 200 ms long photovoltage traces measured on contact $C3$ of sample S1 at different magnetic fields (shown at the curves) and used to obtain the data points presented as symbols in panel (a). The zero levels are shown by dotted lines. The dashed lines on the $B = 95$ mT fragment illustrate the definition of different quantities characterizing the strength of the pulses.

quasistable photovoltage levels are referred to as $\bar{U}_{up}$ and $\bar{U}_{down}$. While the up pulses are essentially flat, in some traces the down pulses exhibit a trapezoidal shape implying a drift of the photovoltage to a larger value after the abrupt reversal. To take into account this difference in the pulse shape, the maximum photovoltage within each of the up pulses and the minimum photovoltage within each of the down pulses were also extracted. Then, averages were built for all pulses: $\bar{U}_{up,peak}$ and $\bar{U}_{down,peak}$. In panel (a) of Fig 1, these averaged peak values (triangular symbols) as well as the time average of the signal across the entire captured time interval, $\overline{U_t}$ (circular symbols), have been plotted as a function of B in the regime where erratic switching is observed. $\overline{U_t}$ resembles closely the photovoltage line trace (solid line) recorded with a multimeter in Fig. 1(a) at a lower power where switching events are absent.

The data in Fig. 1 imposingly demonstrate that the measured photovoltage on sample S1 consists of two contributions which, hereafter, will be referred to as the intrinsic and spontaneous photovoltages. The intrinsic photovoltage oscillates as a function of magnetic field and is available across the entire explored magnetic field range, whereas the spontaneous photovoltage is only present near the primary photovoltage peak. The intrinsic photovoltage has been accounted for by built-in electric fields which occur on a length scale much smaller than the typical sample size [15,18]. These built-in fields stem from the inevitable inhomogeneous distribution of the charge carriers. Such inhomogeneities occur near the contacts due to a difference in the work function of the GaAs heterostructure and the metal alloy forming the contact as well as near the boundaries of the sample due to depletion. An additional source of built-in fields can be disorder due to randomly distributed dopants or impurities, for instance. Under nonequilibrium conditions in a sample exposed to radiation, the Einstein relation between the conductivity and the diffusion constant is not valid anymore [18,19]. The electrochemical potential is no longer constant across the entire sample, and internal voltages appear as a consequence of these built-in electric fields under steady-state conditions. The resulting photovoltage oscillates with B according to the ratio of $\omega_c/2\pi f$ just as the microwave induced resistance oscillations but with opposite phase (for more details, we refer to Fig. SP1 in the Supplemental Material [20]). The second, spontaneous, photovoltage contribution does not originate from sample intrinsic built-in electric fields but, instead, from the Hall electric fields which develop in the zero resistance regime because of spontaneous symmetry breaking and current domain formation when the conductivity goes negative. For this mechanism, only a constant time-independent photovoltage is anticipated. However, the observed switching suggests random transitions between two possible quasistable domain configurations. This switching has been previously studied on sample S2 and reported in Ref. [21]; however, it was not possible to identify a relationship or a correlation between the two quasistable domain configurations. For instance, do both quasistable configurations correspond to two totally different patterns of current domains or do they just differ in the electric field orientation within each domain? Establishing such a correlation was hampered by the strength of the intrinsic photovoltage in sample S2 (see also Fig. SP2 [20]). It was so large, in comparison with the amplitude of the spontaneous photovoltage pulses, tha it was not possible to separate the intrinsic and spontaneous photovoltages and draw conclusions about their variation within this pulse regime. Since the internal electric fields may strongly depend on contact formation details and other disorder (see a more detailed discussion in the Supplemental Material [20]), there is a finite probability of encountering instances where the intrinsic photovoltage only represents a minor contribution to the total photovoltage, so that the time-dependent component attributed to the spontaneous photovoltage dominates. Sample S1, which was not studied previously, satisfies these conditions.

Although the data in Fig. 1, Fig. SP1, and Fig. SP2 clearly demonstrate that the intrinsic photovoltage in sample S1 is much lower than that in sample S2, the maximum change of the photovoltage observed during switching events is, in both samples, close to 2 mV. This key observation supports our assertion that the spontaneous photovoltage emerges as a result of current domain formation independently of the intrinsic photovoltage effect itself. A discussion of parameters that may account for the large difference in the strength of the intrinsic photovoltage magneto-oscillations on the two samples studied here is deferred to the Supplemental Material [20].

The intrinsic photovoltage due to built-in electric fields in sample S1 is only a weak, sublinear function of power in the investigated power range (see Fig. SP1 in the Supplemental Material [20]). The power dependence of the spontaneous photovoltage pulses has been plotted in Fig. 2 for fixed $B = 91$ mT. The switching effect smoothly develops at $P > -15$ dBm and abruptly disappears at $P \approx -6.5$ dBm. Outside this power range, all amplitudes tend to the intrinsic photovoltage. From comparison of its values at the ends of this power range, it can be concluded that the magneto-oscillatory intrinsic photovoltage contribution is only a weak function of power across the covered power range. Hence, it plays only a minor role in the time-dependent data obtained on sample S1.

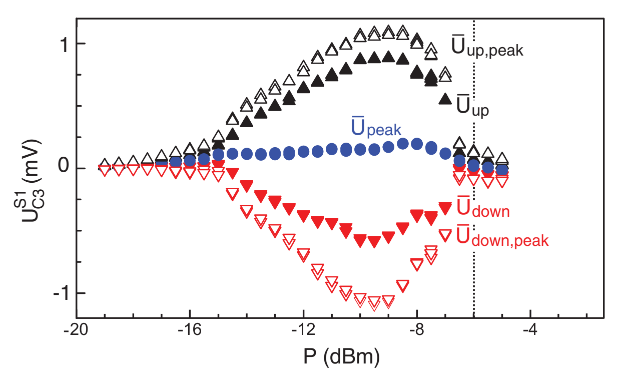

FIG. 2 (color). Average photovoltage quantities $\bar{U}_{up}$, $\bar{U}_{down}$, $\bar{U}_{up,peak}$, $\bar{U}_{down,peak}$, and $\bar{U}_{peak}$ as a function of microwave power recorded on sample S1 at $B = 0.091$ T, $f = 50$ GHz ($2\pi f/\omega_c = 1.3$), across contact $C3$ and an external contact. The dotted line marks the power at which the time-dependent trace in Fig. 1(b) was recorded.

Of particular interest, here, is the obvious correlation between the average peak value of the up and down pulses in the spontaneous photovoltage both in Fig. 1 and Fig. 2. They are not only opposite in sign, but because the intrinsic photovoltage is small and barely depends on the applied power, we can conclude that, to a good approximation, their amplitude is nearly equal and $\bar{U}_{\mathrm{up,peak}} \approx -\bar{U}_{\mathrm{down,peak}}$. In Fig. 2, also, the average value of $\bar{U}_{\mathrm{up,peak}}$ and $\bar{U}_{\mathrm{down,peak}}$, denoted as $\bar{U}_{\mathrm{peak}}$, has been plotted. Its deviation from zero characterizes the accuracy with which the relation $\bar{U}_{\mathrm{up,peak}} \approx -\bar{U}_{\mathrm{down,peak}}$ is satisfied. In the power range from -13 to -7 dBm with pronounced pulses, $|\bar{U}_{\mathrm{peak}}| \ll \bar{U}_{\mathrm{up,peak}}, |\bar{U}_{\mathrm{down,peak}}|$. Because multiple domains may exist in between the contacts used for measurements, the voltage levels do not necessarily provide information about the Hall field within a single domain. However, a natural explanation for the alteration between the observed quasistable voltage levels of opposite sign is that the system switches between two electric field domain configurations which differ only in that the electric field is reversed completely in each domain upon a switching event. This is the key experimental finding in this Letter.

If the above picture holds, then switching events in the spontaneous photovoltage should occur synchronously at different locations of the sample. Figure 3 displays fragments of three time traces measured simultaneously across a contact at the sample perimeter and three internal contacts scattered across sample S1. We note that, in the absence of net current, the sample perimeter is an equipotential line, so that the choice of a specific external contact is irrelevant [15,21]. Indeed, the different photovoltage signals simultaneously switch to a different level. By passing a dc current through an internal contact, we expect to mainly change the electric potential in the contact vicinity due to current spreading. Electric fields far from the contact are only weakly affected. Then, it will increase the "intrinsic" photovoltage while leaving the long-range spontaneous photovoltage unaffected. The outcome of such an experiment is plotted in Fig. 4. The spontaneous photovoltage pulses merely undergo an overall shift as illustrated in Fig. 4(a), but their amplitude remains essentially unaltered as seen in Fig. 4(b) where the average pulse quantities are plotted as a function of the imposed dc current. This confirms that the overall photovoltage is composed of two largely independent contributions. It also implies that the spontaneously formed domain pattern with a characteristic length scale of the sample size is not sensitive to local potential variations. Therefore, we believe that the internal contacts utilized to investigate the photovoltage distribution across the sample do not represent a significant disturbance for the microwave induced domain pattern.

An analysis for sample S2, similar to Fig. 1(a), is included in the Supplemental Material [20]. It exhibits a much larger intrinsic photovoltage [see also Fig. 1(a)]; however, the conclusions are the same: Pulses are only present in a limited B-field range within the zero resistance regime, and the up and down pulses are symmetrically arranged around the nearly horizontal line connecting the intrinsic photovoltage data at either end of the B-field range where pulses appear. In the Supplemental Material [20], we also address the frequency dependence of the quantities characterizing the pulses on sample S1. Once more, $\bar{U}_{\mathrm{up}}(f)$ and $\bar{U}_{\mathrm{down}}(f)$, the $\bar{U}_{\mathrm{up,peak}}(f)$ and $\bar{U}_{\mathrm{down,peak}}(f)$ dependencies appear nearly symmetrical relative to the zero level, especially for the latter quantities. The positions of the extrema in these frequency dependencies coincide for the up and the down pulses again lending support for our assertion that the switching reflects a complete electric field

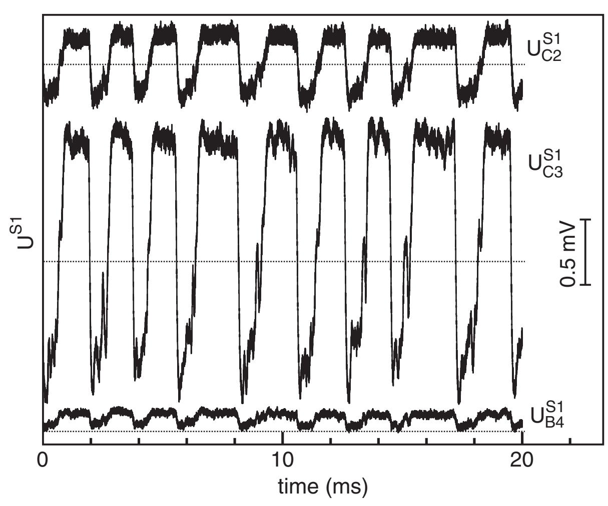

FIG. 3. 20 ms fragments of the 200 ms long oscilloscope traces of the photovoltage recorded simultaneously across three different internal contacts and a contact along the perimeter of sample S1. The signals switch synchronously. Data were recorded at 50 GHz, $B = 0.091$ T ($2\pi f/\omega_c = 1.3$), $T = 1.5$ K, and $P = -9$ dBm.

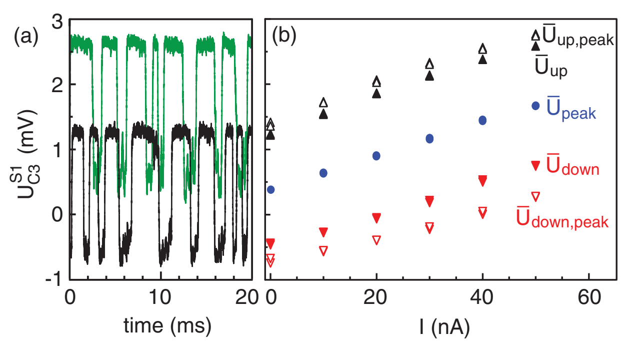

FIG. 4 (color). (a) Fragments of the 200 ms oscilloscope traces of photovoltage U^{S1}_{C3} measured for a dc current $I = 0$ (black curve) and $I = 50$ nA (green curve). (b) Photovoltages $\bar{U}_{\mathrm{up}}$, $\bar{U}_{\mathrm{down}}$, $\bar{U}_{\mathrm{up,peak}}$, $\bar{U}_{\mathrm{down,peak}}$, and $\bar{U}_{\mathrm{peak}}$ measured on contact $C3$ of sample S1 at $f = 40$ GHz versus dc current through this contact for $B = 0.078$ T ($2\pi f/\omega_c = 1.2$), $P = -1$ dBm, and $T = 1.5$ K.

reversal within each domain of the spontaneous domain pattern induced by the microwave radiation.

We conclude that, in the microwave-induced zero-resistance regime, a contribution to the photovoltage arises which exhibits a random reversal. This occurs synchronously at different internal voltage probes. This observation implies the appearance of a spontaneous electric field which flips randomly with time. Passing a small dc current through the internal contact results in the simple addition of a dc voltage on top of the time dependent signal, eventually eliminating a sign reversal of the total photovoltage. We argue that, similarly, the intrinsic photovoltage, originating from built-in electric fields, is additive. Our observation of the electric field flip is consistent with the theoretical domain picture when extended to allow for switching between two domain patterns which merely differ in the electric field sign in each domain. Both field orientations are equally possible in a sample with weak disorder. The existence of two such equally probable patterns is a characteristic feature for domains arising from spontaneous symmetry breaking.

We gratefully acknowledge the support of the Russian Science Foundation (Grant No. 14-12-00599, data analysis) and the German Israeli Foundation.

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[20] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.114.176808 for a (i) comparison of the magneto-oscillations of the photovoltage and resistivity, (ii) the data measured on sample S2, (iii) the frequency dependence of the pulse amplitudes in sample S1, and (iv) a discussion of the possible origin of the difference in the intrinsic photovoltages for the two investigated samples.
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