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Magnetic state dependent transient lateral photovoltaic effect in patterned ferromagnetic metal-oxide-semiconductor films

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We investigate the influence of an external magnetic field on the magnitude and dephasing of the transient lateral photovoltaic effect (T-LPE) in lithographically patterned Co lines of widths of a few microns grown over naturally passivated p-type Si(100). The T-LPE peak-to-peak magnitude and dephasing, measured by lock-in or through the characteristic time of laser OFF exponential relaxation, exhibit a notable influence of the magnetization direction of the ferromagnetic overlayer. We show experimentally and by numerical simulations that the T-LPE magnitude is determined by the Co anisotropic magnetoresistance. On the other hand, the magnetic field dependence of the dephasing could be described by the influence of the Lorentz force acting perpendiculary to both the Co magnetization and the photocarrier drift directions. Our findings could stimulate the development of fast position sensitive detectors with magnetically tuned magnitude and phase responses. [http://dx.doi.org/10.1063/1.4935441]

When a high frequency current is externally injected into a thin metallic wire, its complex response is described in terms of impedance. If the wire is made of ferromagnetic material, the impedance may depend on the magnetic state and the *famous* magnetoimpedance effect is then observed.[1] Here we report on the magnetic-state-driven transient lateral photovoltaic effect, which is analogous to the magnetoimpedance effect but with locally generated photocarriers.

The non-uniform illumination of a semiconductor surface or ultrathin metallic films forming Metal-Oxide-Semiconductor (MOS) structures generates an electric field parallel to the surface or to the Schottky barrier due to a photocarrier drift in non-equilibrium conditions. The straight-forward way to maximize the potential difference is to generate photo-carriers effectively (by using a laser with its photon energy exceeding the gap) with a spot diameter much less than the distance between the asymmetrically situated lateral contacts. This potential difference is known as the lateral photovoltaic effect (LPE).[2–5] On the practical side, the LPE has been widely used to develop high precision position-sensitive detectors (PSD).[6–8] The recent interest in $Co/SiO_2/Si$ structures has been related to their high PSD sensitivity for the visible, ultraviolet or infrared range[9–11] by adjusting the Co thickness.

Advances in electron beam lithography have permitted the development of MOS structures where the LPE can be investigated along patterned, few micron wide, metallic line structures. Recently Cascales et al. [12] have found that the time dependent photovoltaic response along such structures is different from the one observed in the wide LPE devices. Specifically, peak-like transient decay curves which present a sign inversion of the T-LPE in the laser OFF state followed by a nearly exponential relaxation back to equilibrium have been qualitatively explained with a simple model taking into account not only resistance and capacitance, but also the local inductance of the metallic line structure deposited on top of a Schottky barrier.

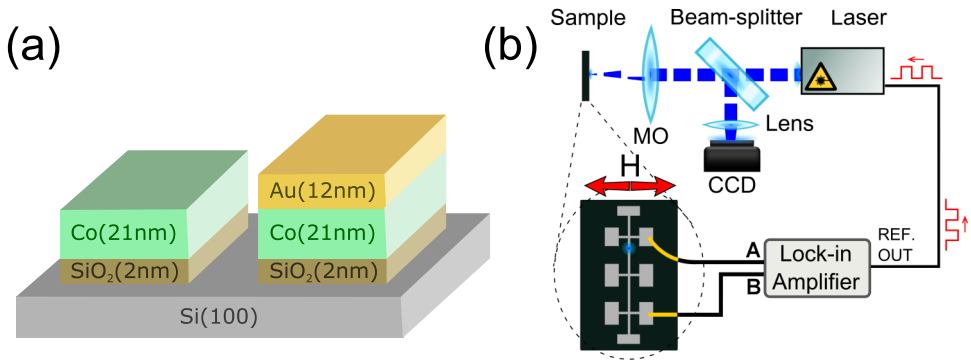

FIG. 1. (a) Layer structure of the two kinds of samples measured. (b) Diagram of the lock-in experimental setup.

Here we investigate the dependence on the magnetic state of both the magnitude and the phase response of the T-LPE, studied by a lock-in technique and by analyzing the relaxation back to equilibrium of the T-LPE time trace, in lithographically patterned (21 nm thick, 10μm wide and 1500 μm long) Cobalt lines (see Fig. 1(a)). The structures were deposited on a naturally passivated (about 2 nm SiO_2) Silicon (100) substrate. More details on the preparation and characterization of samples may be found in Refs. 12–14. A second type of devices have been measured with the addition of a 12 nm Au coating (see Fig. 1(a)).

We have observed and qualitatively explained the substantial influence of the magnetic state of the Cobalt ovelayer on the magnitude and phase of T-LPE. On one hand, numerical simulations and experiments confirm a direct link between the field dependent T-LPE and the anisotropic magnetoresistance. On the other hand, we observe a signal dephasing dependent on the magnetization direction, which could be linked to the inversion of the direction of the Lorentz force acting on the photocarriers drifting along the metallic line structure.

We have investigated the magnetic field dependent T-LPE with two electronically different setups. The first system obtains a direct measurement of the T-LPE characteristics with microsecond resolution and was described elsewhere.[12] A second measurement scheme employing the lock-in technique was used to observe the influence of an external magnetic field on the T-LPE amplitude as well as the phase difference between the reference signal and the T-LPE response at the first harmonic. Such lock-in measurements, with laser pulses modulated by a reference signal in the kHz range, have been previously used to characterize the lateral photovoltaic effect in MOS-type PSDs.[6] The phase of the photovoltage has been shown as alternative, high precision detection method of the position of a signal.[15] The main advantage of such a method is related with its insensitivity to the variation of the incident light intensity. Here we use a similar techique which additionally incorporates the possibility to determine LPE phase changes as a function the external magnetic field.

The optical setup and the electronics used for the measurements is schematically shown in Fig. 1(b), along with a typical sample with contacts. The laser beam is focused onto the sample by a microscope objective lens (MO) (50x, 0.42 NA, Plan APO, working distance 21 mm) and the image of the sample is relayed into a CCD camera by using the objective and a beam splitter. The spot size has a diameter of around 2 μm. When the laser spot is asymmetrically situated with respect to a selected pair of the measurement contacts situated at different lengths of the line, the potential difference due to the T-LPE periodically appears between those contacts (see Ref. 12 for details). The potential difference created along the line is measured by contacting the selected pair of 500×500 μm^2 Cobalt pads to the amplifier via gold contacts fixed to the pads by indium. The T-LPE has been studied by applying a train of periodic laser beam pulses, with a power between 0.7-3 mW which are modulated by a reference signal (typically of 787 Hz). The electronic setup which obtains the time trace of the transient LPE response was described elsewhere.[12] The second experimental technique consists on feeding the LPE voltage as the input into a lock-in so the magnitude and phase of the voltage at the reference frequency are registered. A TOPTICA-iBeam Smart diode laser which emits light of 487 nm of wavelength λ has been used. The optical setup

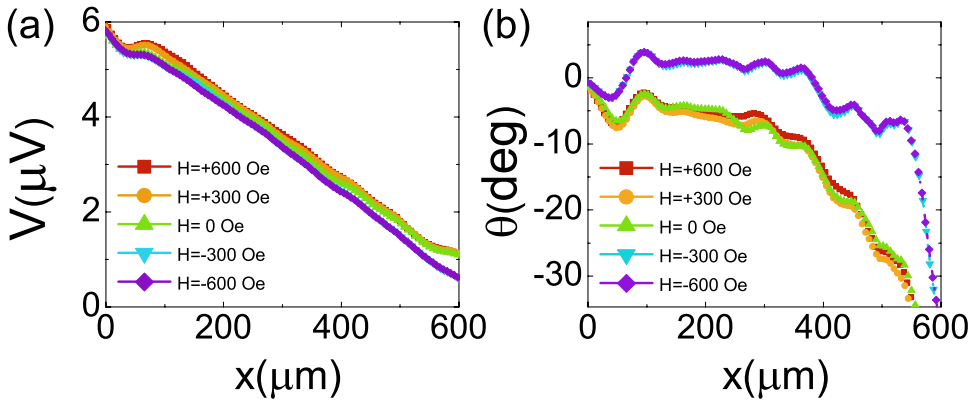

FIG. 2. (a) Amplitude and (b) phase of the signal registered by the lock-in as a function of the distance from one end of the sample for a laser power of 2.8 mW at different external magnetic field values.

is common to both electronic detection methods. An in-plane magnetic field perpendicular to the Cobalt line is applied by two Helmholtz coils as is schematically shown in Fig. 1(b).

A typical T-LPE response when the device is subjected to a periodically modulated light beam shows peak-like transient decay curves presenting a sign inversion in the OFF state.[12] The OFF state peak is followed by a nearly exponential relaxation back to equilibrium. The peak-to-peak amplitude (A_{pk-pk} and the characteristic time τ_{OFF} of the laser OFF exponential relaxation will be discussed further below.

Let us now discuss the analysis of the lock-in measurements. As can be seen in the main part of Fig. 2(a), the magnitude depends linearly on the position of the laser spot (typical LPE behaviour). If we take the phase θ at one end of the device ($x = 0$) as the reference, then the phase of the signal can be seen to deviate from 0 as the laser spot moves away from the positive electrode (Fig. 2(b)). This change in phase is due to the change in distance that the signal has to travel to reach the electrode as the laser spot is moved. Even though our sample has a total length of 1.5 mm, the dependence of the phase on the position presents a similar behaviour as in Ref. 6 (where the sample size is of the order of a cm), although the total phase change of around 60 ° is somewhat smaller.

We next discuss the dependence of the voltage and phase on the position in the presence of an external magnetic field. As can be seen in Fig. 2(a) and 2(b), the voltage amplitude presents a close to linear dependence on the position (consistent with the T-LPE) while an abrupt change in the phase occurs for fields close to the field where the Co lines exhibit an AMR peak (see below). This behaviour has been consistently observed in our samples.

As can be seen using the lock-in technique, we find the change in magnitude due to the magnetic field being less than 3%. Therefore, we used a more sensitive T-LPE measurement technique to determine with higher precision the influence of the magnetic state of the Co lines the possible variation of both magnitude and characteristic relaxation back to equilibrium as a function of the magnetic state of Co lines.

The variation of an external magnetic field has been also found to influence both the magnitude A_{pk-pk} and the relaxation time τ_{OFF} of the laser OFF transition. Figure 3(a) presents an analysis of τ_{OFF} *vs.* H for a full field cycle. The relaxation time τ_{OFF} was obtained by fitting an exponentially decaying function to the decaying part of the OFF peak (inset of Fig. 3(a)). As can be seen, the relaxation time for negative fields is noticeably lower than for positive fields, and a step-like transition between both regimes is seen close to the switching field of the Co line, known from AMR measurements. We should note that the branches do not meet at the starting point (positive saturation field). This is due to the fact that the measurements take a considerable amount of time to carry out (a few hours), and the temperature conditions could slightly change during the measurement.

The experimentally observed variation of the T-LPE dephasing with the direction of the magnetization may be qualitatively explained by the toy model shown in Fig. 3(b). For a fixed direction of the velocity of the charge carriers, depending on the direction of the applied field, the resulting

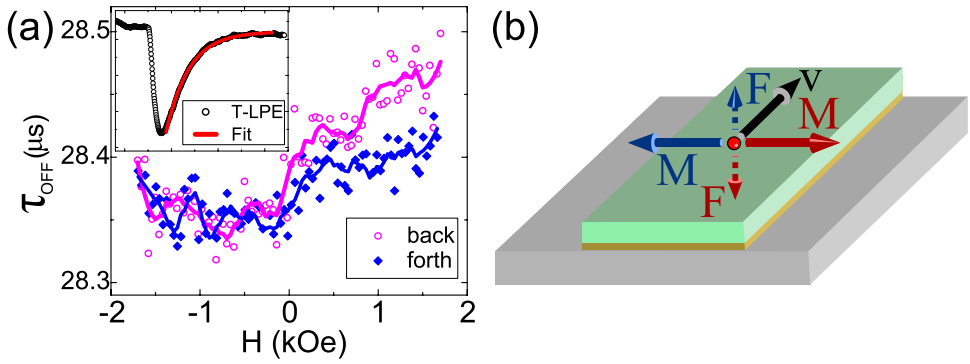

FIG. 3. (a) Dependence of the laser OFF relaxation time on the external magnetic field for a 10 μm Co line. The inset presents the exponential fitting done to estimate τ_{OFF}. (b) Diagram representing change in direction of the Lorentz force acting over photocarriers due to an inversion of the magnetization of the ferromagnet.

Lorentz force may shift the carriers upwards or downwards. If the magnetic field forces the carriers downwards, this will promote the recombination processes, accelerating the decay of the laser OFF peak. Conversely, if the recombination process is delayed because the carriers remain in the Co for a longer time, τ_{OFF} will increase.

Our observations suggest a further modification of the drift-diffusion equation when the metallic overlayer is made by a thin and narrow feromagnetic films,[12] where the resistance (R), effective capacitance (C) and inductance (L) of the metallic line becoming potentially magnetic field dependent, i.e. $L(H)\frac{d^2u(x_0,t)}{dt^2} + R(H)\frac{du(x_0,t)}{dt} + \frac{1}{C(H)}u(x_0,t) = F(x_0,t)$ where $u(x,t)$ is the potential distribution, x_0 the laser spot position and $F(x_0,t)$ the electron-hole generation function. On one hand, the present experiments and simulations clearly show, in agreement with recent studies of stationary LPE by Wang et al.,[17] that the magnitude of the LPE could be magnetically controlled through a magnetic field dependent resistance $R(H)$ originated from the lateral photoeffect and the anisotropic magnetoresistance (Figs. 4(b)). On the other hand, our observation of a slow relaxation time and dephasing dependent on the magnetic state indicate that in the present experimental conditions with an in-plane magnetic field perpendicular to the ferromagnetic line structure, the main influence of the Cobalt magnetic state on the T-LPE dynamics should be atributed to changes in the effective capacitance $C(H)$.

As a further step to clarify the possible influence of the external magnetic field on the T-LPE magnitude, we carried out magnetoresistance measurements, with the applied field in plane and perpendicular to the Co line. Both experiments are done by cycling the field from a positive saturation value down to a negative saturation value (back branch), and back to the positive saturation field (forth branch). Resistance measurements as a function of the field reveal anisotropic magnetoresistance (AMR) effects. The AMR of the Cobalt line was found to present a peak at low fields (around 20-30 Oe), with a maximum AMR ratio of 0.6% as can be seen Fig 4(a). This is a well-known effect in ferromagnets when the local magnetization interacts with an electron current, depending on the relative angle between the local magnetization and the direction of the current (see the Supplemental Material[16]).

We have found that the T-LPE amplitude is enhanced by 0.6% (see Fig 4(b)), at fields which correspond to the maximum in AMR of the Co line devices. We define this effect as Anisotropic Transient Lateral Photovoltaic Effect (A-T-LPE). If the MOS system is coated with gold, the absolute values of the A-T-LPE are reduced almost by half due to the increment of absorbed light and increment of the conductance. More details regarding the gold-coated samples can be found in the Supplemental Material.[16] These observations indicate that the T-LPE peak-to-peak amplitude variation with an applied magnetic field is directly related with anisotropic magnetoresistance.

We support this conclusion by micromagnetic simulations and numerical simulations. In Figure 4(c) a calculated magnetoresistance curve is shown, indicating the same qualitative behavior

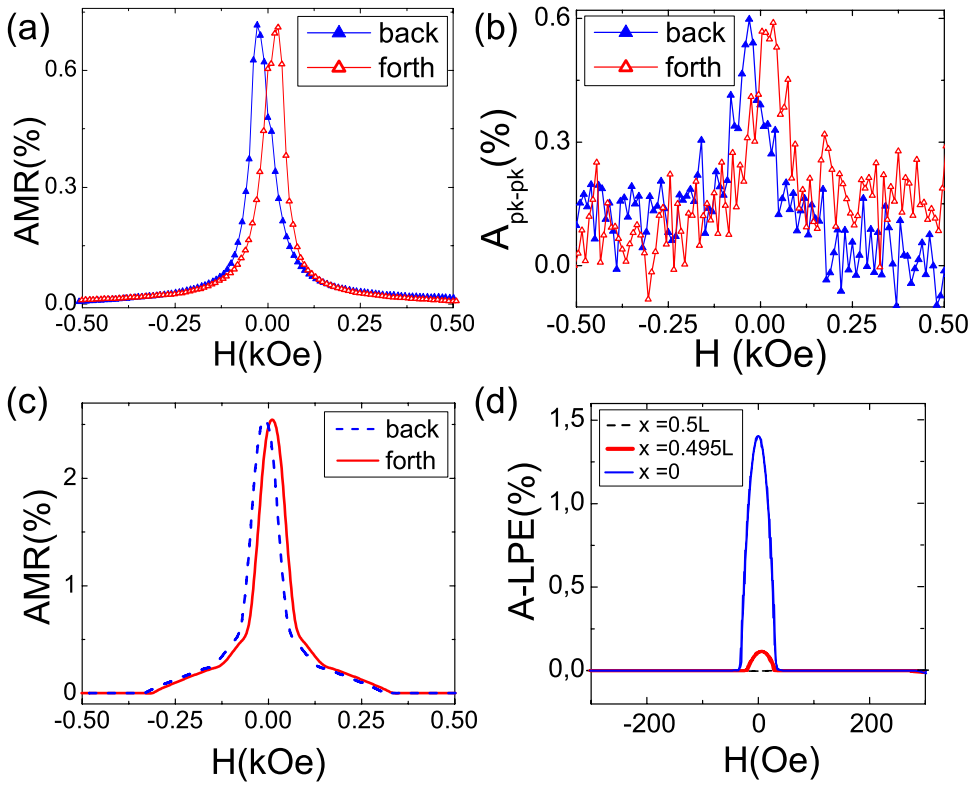

FIG. 4. Comparison of the (a) anisotropic magnetoresistance and (b) anisotropic lateral photovoltaic effect for a 10μ m wide Cobalt line. (c) Simulated AMR of a stripline with field applied perpendicular to the line. (d) Simulated increase in the LPE potential generated by the laser due to the AMR for different positions of the laser spot.

as the measured one. A larger remanence can be achieved in the simulations by artificially introducing disorder (see Supplemental Material[16]). For a second type of simulation, the induced voltage created by photocurrents moving away from the laser spot is considered for different positions x with respect to one of the contacts. Fig. 4(d) shows this fact for the case of a laser excitation at the same distance of each contact (black dashed line, zero signal) and at different distances from each contact (non-zero response), expressed in units of the line length L. All the non-zero signals are found at low fields, when magnetoresistance is high, due to the presence of domains in the unsaturated sample, just like in measurements. This suggests the strong influence of magnetoresistance in the signal measured as a function of field. Further explanations of the simulation methods can be found in the Supplemental Material.[16]

To sum up, we have studied the influence of the magnetic state of a ferromagnetic overlayer on the transient lateral photovoltaic effect in 10 μm wide Co/SiO_2/Si line structures. Two different experimental methods, (i) a direct time dependent response with microsecond resolution and (ii) a lock-in technique, have been used to investigate the possible changes in dephasing of the T-LPE with magnetization direction. For the lock-in measurements, we compare the LPE magnitude and phase in each spatial point along the Co line structure at different values of the external field with the results at the saturation field (2 kOe). This allows observing the dependence of the phase as a function of the Co magnetization direction relative to the drift velocity of the relaxing photo-carriers. An abrupt variation of the phase with the inversion of the magnetization direction has been explained with a simple model considering the inversion of the direction of Lorentz force acting on drifting photo-carriers as a consequence of the inversion of the Co magnetization (see the sketch in Fig. 3(b)) explaining the effect in Figure 2(b)). Independent experimental studies involving the analysis of the influence of magnetization direction on the characteristic relaxation time (back to equilibrium) shown in Figure 3(a) support the above simplified model. Our experimental

results could point to having magnetic field dependent R, L, C parameters of the device in the drift-diffusion model presented in Ref. 12. Future experiments should investigate the influence of different (longitudinal) magnetic field configurations and explore the practical aspects of tuning the PSD sensitivity by magnetic fields in Ferromagnetic/Oxide/Semiconductor structures.

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