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To control the semiconductor device under low magnetic field is still a great challenge for semiconductor magnetoelectronics. In this work, we report the observation of the magneto-photogalvanic effect in periodic GaAs dot arrays. With an increase in magnetic field from 0 to 1500 Oe, the photovoltage increases linearly for a wide temperature range from 80 to 430 K. Compared with GaAs without the dot arrays, periodic GaAs dot arrays have a hundredfold increase of the magnetic-field-modulated photovoltage at room temperature. By changing the magnetic field orientation, the angular dependence of photovoltage reveals that the magneto-photogalvanic effect stems from the Hall electric field caused by optical current, and the enhancement of magneto-photogalvanic effect is attributed to the *p-n* junction coupling between GaAs dots. When the coupling between the GaAs dots is broken at the high temperatures, i.e., $T = 430$ K, we demonstrate that the enhancement effect disappears as expected. Our results not only illustrate the magnetic control of energy flow in light harvest, but also provide an applicable way for semiconductor magnetoelectronics by utilizing *p-n* junction coupling. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4971406]

With the continuous shrinking to meet the projections of Moore's law, semiconductor electronics is now reaching its fundamental limits.[1] To realize, Magnetic-field-manipulated semiconductor electronics is promising for future magnetoelectronics, which naturally combines modern electronics with magnetic functionalities.[2] So far, various semiconductor materials from narrow gap semiconductors such as Ag_2Te/Se,[3–5] InSb,[6] and WTe_2[7–9] to conventional and commercialized semiconductors such as GaAs,[10] Ge,[11,12] and Si[13–15] all have shown that the electric transport behavior can be significantly modulated by the magnetic field, which yields an unexpectedly large and unsaturated magnetoresistance (MR). These pioneer works open an era of semiconductor magnetoelectronics without using ferromagnet. Compared with the nowadays magnetoelectronics based on ferromagnet, the semiconductor magnetoelectronics could provide the larger MR with the higher MR sensitivity. For example, MR for WTe_2 is as high as 452 700% at 4.5 K in a magnetic field of 14.7 T, which yields the MR sensitivity up to 3079% per kOe.

Recently, optoelectronics, being another fundamental application of semiconductor electronics, has been reported that it can also be significantly modulated by the magnetic field.[16] It was discovered that by the combination of the magnetoresistance of ferromagnet FeNi (or NiCo) and the photoelectric effect of Si Schottky junctions, it is possible to realize the magnetic tuning of the photovoltage in FeNi/Si Schottky junctions. By applying a very low magnetic field on the order of oersteds, the ratio of lateral photovoltage change in Si can achieve 3.2%, compared to the value of 1.1% in NiCo. Although the photovoltaic effect under the low magnetic field is caused by the change of magnetic moment of the ferromagnet, it should be noted that the ratio of photovoltage change in Si is counterintuitively much larger than that in ferromagnet NiCo. This immediately leads to the question of whether photovoltage is possible to be manipulated by the low magnetic field from the semiconductor without the auxiliary ferromagnet, especially in the *p-n* junction, which naturally has combined a well-known excellent photoelectric effect and a large MR effect.[17–19]

In this work, we fabricated the GaAs devices patterned periodic dot arrays by ion implantation. Due to the concentration difference, each GaAs dot in arrays can be considered as a single *p-n* junction. Remarkably, we demonstrate that the photovoltage in GaAs with dot arrays increases linearly with the magnetic field from 0 to 1500 Oe, which is two orders amplitude larger than that in GaAs without dot arrays. The temperature dependence of photovoltage further reveals that the enhancement of the magneto-photogalvanic effect stems from the form of coupling between dot arrays, when the carrier diffusion length is comparable to the distance of the GaAs dot arrays. Since *p-n* junction is one of the most fundamental building blocks in modern electronics, the magneto-photogalvanic effect in *p-n* junction under the low magnetic field offers a tantalizing prospect of incorporating magnetic, optical, and electronic functionality together.

We selected the single crystal semiconductor GaAs [100] to study the magneto-photogalvanic effect. Unlike the indirect band gap of Si, GaAs is known as a direct band gap semiconductor, where the electrons can be directly excited by photons. In order to fabricate the *p-n* junction arrays, we

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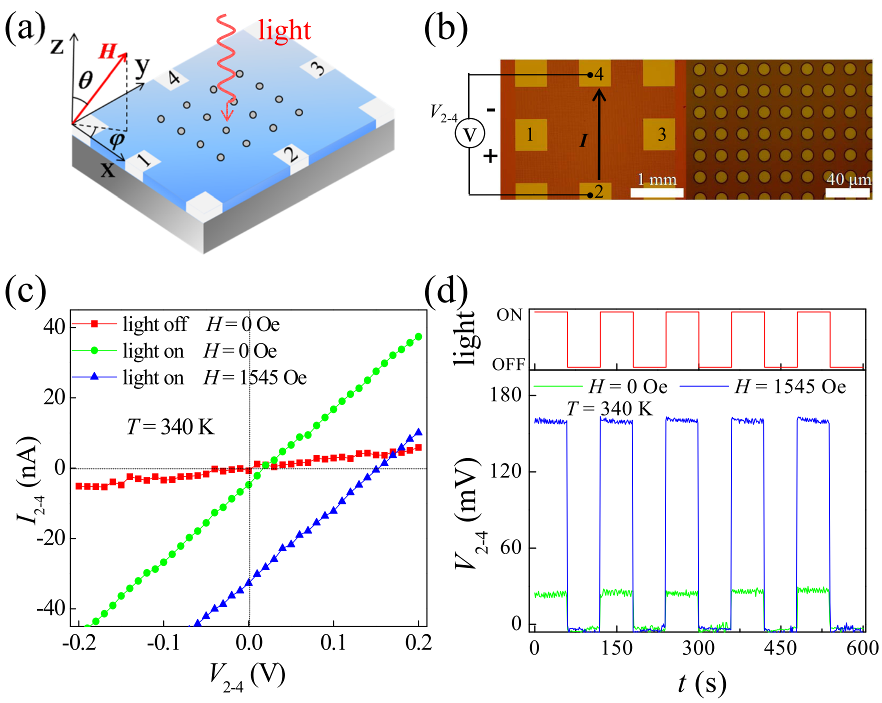

FIG. 1. (a) The sketch of the fabricated GaAs device with dot arrays. (b) The left figure is the optical microscopy image of sample, and the right figure is the higher magnified dot array image. (c) The curve of current-voltage characteristics is manipulated by the magnetic field. The measurement configuration is shown in (b). We apply the current from electrode 2 to 4, and measure the voltage between electrode 2 and 4. (d) Schematic of the laser pulse sequence and open-circuit photovoltage measurements. In both (c) and (d), the magnetic field is directed by the *y* axis.

implanted nitrogen ions (40 keV, 1×10^{17} atom/cm^3) at the top surface of GaAs, where dot arrays were patterned by lithography technology. The fabrication method is compatible with the semiconductor CMOS technology. The experimental work was carried out at the 320 kV platforms for multi-discipline research with highly charged ions at the Institute of Modern Physics, Chinese Academy of Sciences. Figure 1(a) shows the sketch of the fabricated GaAs device with dot arrays. A laser beam with a wavelength of 650 nm and a power of 30 mW was used to illuminate dot arrays of the sample. The open-circuit photovoltage (V_{oc}) was directly measured between Ag electrodes. For brevity, we refer to the voltage between electrodes 1–3, 2–4, and 1–4 as $V_{1\text{–}3}$, $V_{2\text{–}4}$, and $V_{1\text{–}4}$, respectively. The optical microscopy image of GaAs device with dot arrays is shown in Fig. 1(b). The centre to centre distance of the dot is 20 μm, and the dot diameter is 10 μm. In supplementary material, Fig. S1, we further present the n^+-GaAs dot arrays by mapping the distribution of nitrogen concentration.

Figure 1(c) shows the typical magneto-photogalvanic effect in periodic GaAs dot arrays at 340 K. For the GaAs without illumination, we did not observe the rectifying behavior. The current (*I*)-voltage (*V*) curve exhibits a linear characteristic, which indicates that the lateral space charge region between each dot is weak. Even when the sample is illuminated by light, the *I–V* curve still keeps the linear behavior, but the sample resistance decreases from 30 to 4.6 MΩ due to photo-induced carriers. We also check that the open-circuit photovoltage is only 22 mV, which is consistent with the weak lateral space charge effect. However, here V_{oc} significantly depends on the magnetic field. When the magnetic field is applied, *I-V* curve exhibits an obvious shift along the voltage axis. At $H = 1545$ Oe, V_{oc} significantly increases from 22 to 155 mV. To further demonstrate such magneto-photogalvanic effects, we recorded the photovoltage cycles with and without the magnetic field by consecutively switching the light, as shown in Fig. 1(d). One can find that V_{oc} is 22 mV at $H = 0$ Oe, however, at $H = 1545$ Oe, the V_{oc} is enhanced to 156 mV.

In Fig. 2, we present the magnetic tuning open-circuit photovoltage effect at the room temperature. It is worth noting that the photovoltage $V_{2\text{–}4}$ increases linearly with increasing magnetic field from 0 to 0.15 T, but the slope, defined as magnetic sensitivity dV_{oc}/d*H*, is dependent on the orientation of the magnetic field. In Fig. 2(a), during rotation of magnetic field in the *xy* plane, the maximum value of

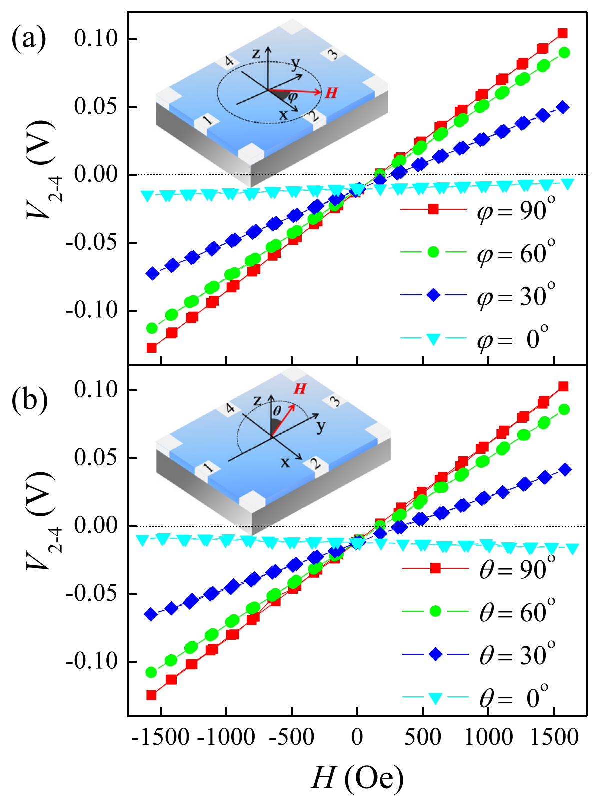

FIG. 2. Open-circuit photovoltage $V_{2\text{-}4}$ as a function of the magnetic field at room temperature. (a) *H* in the *xy* plane. (b) *H* in the *yz* plane.

slope (~74 μV/Oe) is observed as the magnetic field oriented perpendicular to the x axis, and the minimum value of slope (~2.7 μV/Oe) occurs as the magnetic field parallel to the x axis. The similar results are observed during the rotation of magnetic field in the yz plane, as shown in Fig. 2(b). Interestingly, compared with the obvious MR in previous semiconductors, which require a working magnetic field of Tesla magnitude,[17–19] the working magnetic field of magneto-photogalvanic effect is only needed in Oersteds magnitude. Remarkably, the linear feature in a low magnetic field makes such magneto-photogalvanic effect more attractive to magnetic sensor industry. For comparison, we also measured the magnetic tuning open-circuit photovoltage to the GaAs device without dot arrays (see Fig. S2 in the supplementary material). It shows that the magnetic sensitivity of photovoltage for the GaAs device without dot arrays reduces two orders of magnitude, which suggests that the dot arrays may play an important role in the enhancement of magneto-photogalvanic effect.

Figure 3 shows the anisotropic magneto-photogalvanic effect of the GaAs device with dot arrays at room temperature. One can find that all curves can be described well by the sinusoidal function. In Fig. 3(a), during rotation of magnetic field in the xy plane, when the measuring electrodes are changed, the sinusoidal function exists as obvious phase shift, but keeps the same amplitude. Whereas, in Fig. 3(b), during rotation of magnetic field in the yz plane, the sinusoidal function exists as obvious amplitude change, but keeps the same phase. Remarkably, when the magnetic field parallels to the z axis, the V_{oc} is zero value. Hence, the whole angular dependence of magneto-photogalvanic effect can be formulated by a simple equation

$$E = E_0 + \alpha z \times H, \quad (1)$$

where E_0 represents the photoelectric field at zero magnetic fields, and α is the fitted parameter of linear relationship between the magnetic field and photovoltage.

According to Eq. (1), the photovoltage can be well explained by the Hall electric field, if we consider that the optical current flows along the z axis. As shown in Fig. 4(a), the space-charge region is formed at the interface between n^+-GaAs and the GaAs substrate. When light illuminates the surface of the device, electron-hole pairs are generated in the doped dot area of the GaAs surface due to the absorption of photons. Then, the generated carriers will diffuse from the surface. The holes will be swept through the space-charge region and drag the electrons to cross the barrier of space-charge region. As a result, considering the dynamic balance between carriers diffusion and recombination, the optical current in bulk GaAs is generated along the z axis, but the total optical current is still zero, i.e., $I_e = -I_p$. The photovoltage manipulated by the magnetic field can be ascribed to two mechanisms, as shown in Fig. 4(b). One is that the magnetic field can help the electron-hole pair separation due to the opposite Lorentz force for electron and hole, which increases the diffusion flow of carriers. The other is that the Hall voltage is generated when the diffusion flow of carriers is deflected by the magnetic field, which is consistent with the previous reported magneto-photogalvanic effect.[20]

However, this picture cannot explain a hundredfold increase of the magnetic-field-modulated photovoltage in periodic GaAs dot arrays. Next, we will further discuss the origin of the photovoltage enhancement. According to the above explanation, a hundredfold increase of photovoltage in periodic GaAs dot arrays indicates that the optical current generated in periodic GaAs dot arrays should be two orders amplitude larger than that of the GaAs without the dot arrays, and such optical current enhancement should be closely related to the dot arrays. Therefore, in Fig. 4(b), we use two dots to represent the dot arrays to analyze the optical current. When the carrier diffusion length is comparable with the gap between the two dots, a recombination current is generated. In this situation, a total optical current is divided into two parts. One is the recombination current I_r in the n^+ dot region, and the other is the optical current I_o in

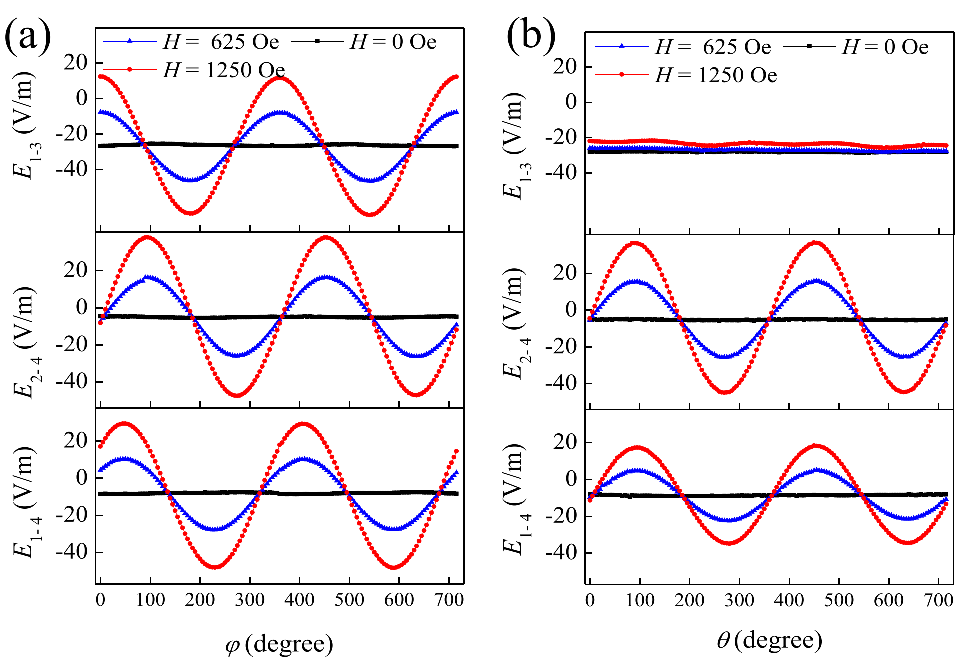

FIG. 3. (a) The angular dependence of photovoltage of GaAs with dot arrays when the magnetic field is orientated in the xy plane. (b) The angular dependence of photovoltage of GaAs with dot arrays when the magnetic field is orientated in the yz plane.

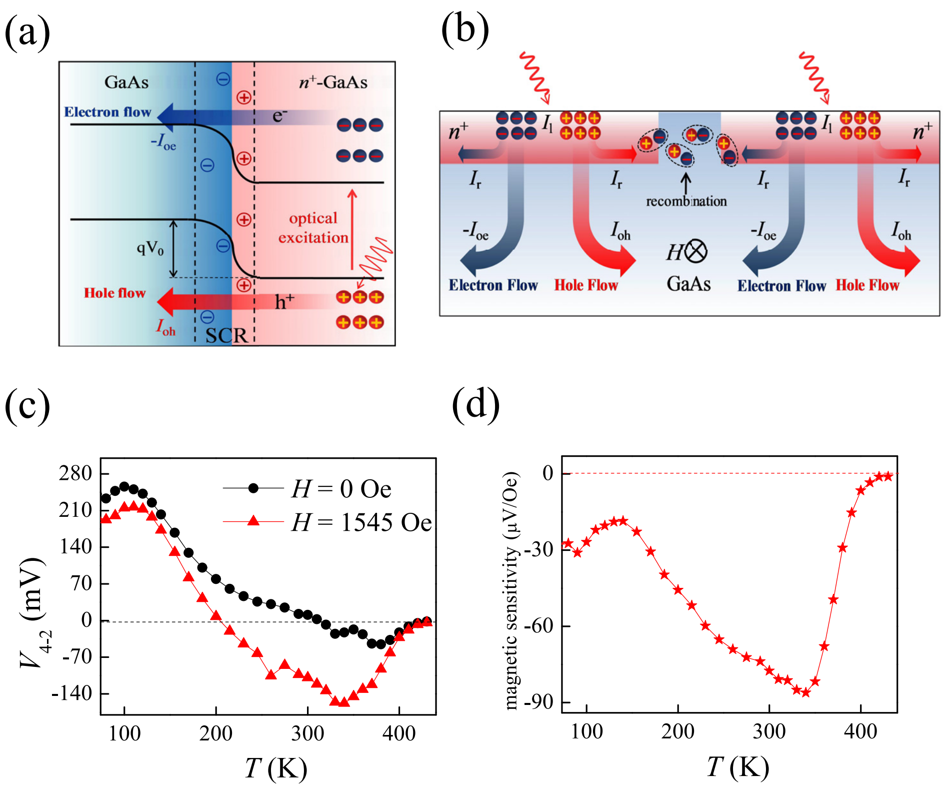

FIG. 4. (a) The schematic diagram of band structure during optical excitation between the doped GaAs dots and GaAs substrate. The dash lines are the boundaries of space-charge region (SCR). (b) The schematic diagram of enhanced magneto-photogalvanic effect for GaAs dot arrays due to charge separations under magnetic field. (c) The photovoltage of GaAs dot arrays as a function of temperature. (d) The magnetic sensitivity of GaAs dot arrays as a function of temperature.

the n region. Interestingly, according to our results, I_r can significantly control the optical current I_o in our device. For GaAs device without the dot arrays, I_r can be considered as 0, thus I_o is also small. Whereas for GaAs device with the dot arrays, I_r occurs, which causes the amplification of I_o. Such an effect is quite similar to the amplification of transistor, where the emitter current is amplified by the base current. In our device, analogous to the transistor, the emitter current corresponds to the light-induced carriers I_l in the n^+ region, the base current corresponds to the recombination current I_r, and the collector current corresponds to the optical current in n region I_o.[21] In order to observe an obvious current amplification effect, the base region in transistor should be designed narrow enough, which can decrease the recombination of the injected carriers in the base region and increase the transmission. In our device, the base region is considered as the doped n^+ region, which is only 0.06 μm according to the implanted energy[22] and satisfies the above requirement. More interestingly, instead of the electric field to control the base current in conventional transistor, the magnetic-field modulated base current is realized by utilizing the Lorentz force to control the charge separation in the n^+ region, as shown in Fig. 4(b). Therefore, the whole device without the external electrical power can be considered as an optical self-amplification system due to the p-n junction coupling.

In order to confirm this picture, we measured the magneto-photogalvanic effect by varying the temperature from 80 to 430 K. This is because the temperature can change the carrier mobility, and thus tune the coupling of dot arrays. Figure 4(c) shows the temperature dependence of V_{4-2} with and without the magnetic field. One can find that the magneto-photogalvanic effect reaches the maximum at 340 K and when the temperature further deviates from 340 K, this effect gradually decreases. It is worth noting that all the photovoltages increase linearly with increasing magnetic field for the whole measured temperature range. So, we can use the temperature dependence of magnetic sensitivity to describe temperature induced magneto-photogalvanic effect, as shown in Fig. 4(d). The magnetic sensitivity decreases with increasing temperature from 80 K, then reaches the minimum at 340 K, and finally sharply approaches to zero as the temperature further increases. Below, we will discuss the temperature effect of magnetic sensitivity by using the coupling of dot arrays. In the high temperatures, because the electron mobility rapidly decreases, the coupling of dot arrays is broken, which indicates that the recombination current I_r between the dots tends to be zero, thus I_o also decreases. Therefore, the magnetic sensitivity sharply approaches to zero in the high temperatures. In the low-temperature region, the coupling of dot arrays is greatly strengthened, all scattered dots can be considered as a whole, which is analogous to the GaAs device without dot arrays. So, the recombination current I_r is also zero, and the absolute value of magnetic sensitivity will gradually decrease as expected. In order to further confirm this picture, we further present the magneto-photogalvanic effect of GaAs samples with dot spacing from 15 to 60 μm, as shown in the supplementary material, Fig. S3. Based on our experimental results, it is more reasonable to attribute the enhancement of magneto-photogalvanic effect to the coupling of dot arrays.

In conclusion, according to the current amplification effect of transistor, we design an optical self-amplification GaAs device with dot arrays due to the p-n junction coupling. The photovoltage of GaAs device presents a linear feature in the magnetic field of Oersteds order, and the magnetic sensitivity is two orders of amplitude larger than that GaAs device without periodic dot arrays. Our work suggests that it is possible to open up opportunities in semiconductor optoelectronics, which can be modulated by the magnetic field.

See supplementary material for the mapping image of n^{+}-GaAs dot arrays, the photovoltage of the GaAs device without dot arrays and the photovoltage of the GaAs device with various dot spacing distances.

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