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Analytical modeling of symmetry breaking in extraordinary optoconductance

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Abstract

Extraordinary optoconductance (EOC) devices with symmetric leads have been shown to have a symmetric positional dependence when exposed to focused illumination. While advantageous for a position sensitive detector (PSD), this symmetric positional dependence, when the device is uniformly illuminated, leads to a minimization of the output voltage. Here, with the aid of a previously employed point charge model, we address two ways to break the symmetry and recover the output signal. The first is to impose uniform illumination but only on half the sample. This method has practical limitations as the device is miniaturized to the nanoscale. The second is via asymmetric placement of the voltage probes in a four-probe measurement. Crucial to the discussion is the effect of the surface charge density. Several ways of modeling the induced surface charge density are presented. Utilizing the above described approach, optimal asymmetric lead positions are found.

Keywords

A. Semiconductors; A. Metal; D. Photoconductivity and Photovoltaics; D. Electronic Transport

Introduction

Extraordinary optoconductance (EOC) was discovered in 2004 as a topological and geometric enhancement to an optically generated signal.ⁱ EOC is the third geometrically driven extraordinary effect, following extraordinary magnetoresistance (EMR)ⁱⁱ and extraordinary piezoconductance (EPC)ⁱⁱⁱ. The EOC phenomenon, typical of the general class of “EXX” sensors^{iv}, is characterized by a comparison of a semiconductor sample (bare device) to an identical sample with the addition of a metal shunt (metal-semiconductor hybrid (MSH) or simply hybrid device) both of which are shown schematically in the inset of Fig. 1. The underlying physics of the position and temperature dependence of EOC was first explained using a point charge modelⁱ and later using a minority hole drift diffusion model^v. It was shown that the EOC effect is due to the differential mobilities of the photogenerated electrons and holes via the Dember effect^v.

One use of such optical sensors is in detecting biologically relevant properties of cells^{vi}. This is typically achieved either with contrast agents that absorb or fluoresce light or via optical

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transmission and reflection spectroscopy. The primary goal in such applications is to minimize the EOC device dimensions in order to maximize spatial resolution while simultaneously maximizing the signal output. However, as the sensor is miniaturized to the micrometer regime and beyond, the optical exposure necessarily becomes more and more uniform. With uniform illumination across the whole device, both the bare and hybrid devices have negligible photo signal. In the case of extraordinary magnetoresistance or EMR^{vii}, a magnetic bit was shown to exhibit similar positional symmetry which could be broken by lead placement but no effort was made to optimize the lead arrangement.

In the case of EOC, the aforementioned symmetry-induced signal minimization can be ascertained from Fig. 1 which shows both the experimentally measured positional dependence of the output as well as a theoretical fit to that data (see below). Uniform illumination of the device corresponds to an integration of the curve in Fig. 1 over the range $0 - X_{\max}$ where $X_{\max}$ is the length of the sample. Such an integration will clearly yield a very small output. Here, for ease of calculation and to highlight the relevant physical processes, an analytical model is employed to assess and optimize EOC device design that breaks the symmetry associated with uniform illumination. The inset for Fig. (1) shows the relevant parameters used in the model. While experimentally the device dimensions, $X_{\max} = 10$ mm, $Y_{\max} = 2$ mm, and lead position $x_1 = 3.4$ mm and $x_2 = 6.6$ mm are fixed, theoretically, the ratio of $X_{\max}/Y_{\max}$ and the full range of x_1 and x_2 can be explored.

Theoretical Model

The EOC is defined as the percent difference in the measured output voltage of the MSH, V_{MSH} , as compared to that of the bare device, V_{bare} , such that

$$EOC(x_1, x_2, y_s, Y_{\max}) = \left\{ \frac{V_{\text{MSH}} - V_{\text{bare}}}{V_{\text{bare}}} \right\} \cdot 100(\%). \quad (1)$$

Here, x_1 (x_2) is the position of the first (second) voltage lead. $Y_{\max}$ is the dimension of the semiconductor in the y direction as shown in the inset to Fig. (1). The parameter, y_s , determines the surface charge density profile generated by the laser and will be discussed in detail below.

A two-dimensional model is justified as follows. First, using the relative dielectric constant for GaAs^{viii} and a wavelength of 476.5 nm, the skin depth of the laser can be calculated^{ix} and is found to be of order 100 nm. This distance and the typical device thickness (400 μm) are small compared to other length scales ($X_{\max} = 10$ mm). Second, the carriers that diffuse perpendicular to the surface contribute negligibly to the photovoltage. As the scale of the device becomes comparable to the length scales previously mentioned, a more robust model will be required which also takes into account ballistic transport.

Because EOC is a ratio of the outputs of the hybrid and bare samples, it is essentially a reflection of the effect of the topographical and geometrical differences in the devices and is not a measure of the magnitude of the output voltage. Geometrically, as only the ratio of $Y_{\max}$ to $X_{\max}$ is important, $X_{\max}$ is fixed at 10 mm for this study. The photo generated voltage, V_{12} , defined as the potential difference between x_1 and x_2 has also been shown experimentally to be independent of the bias current and linear with the power density^v, and therefore these parameters will not be discussed further.

The point charge model is the two dimensional integral of $\sigma(y)$, the surface charge density generated by the incident light at a laser position (x, y) . V_{12} is calculated as the integral of the surface charge density over the distance to the charge,

$$V_{12}(x_1, x_2) = \frac{1}{4\pi\epsilon_o} \int_0^{X_{\max}} \int_0^{Y_{\max}} \sigma(y) \left[\frac{1}{\sqrt{(x-x_1)^2+y^2}} - \frac{1}{\sqrt{(x-x_2)^2+y^2}} \right] dx dy. \quad (2)$$

Discussed below are two ways of modeling the function $\sigma(y)$. While an x -dependence could, in principal, be incorporated into $\sigma(y)$, the only physical basis for this would be an asymmetry in the lead positions. Experimentally, the shunt does play a role in the x -dimensional voltage dependence as evidenced by the quantitative differences in $V_{12}(x)$ exhibited by the bare semiconductor and MSH[†]. The net scale factor, σ_o (see discussion below), of $\sigma(y)$ is fixed by a comparison to x -positional data as shown in Fig. 1 with Eq. 2. As the illuminating laser beam is defocused, a broadening of the peaks occurs culminating in uniform illumination where the net signal is $\sim$ zero. This is due to the symmetry both in the illumination and the lead position. The charge generated by the focused laser beam obeys the superposition principle, thus uniform illumination is a summation of the voltages generated by a tightly focused beam at each x position or equivalently an integration of the x -positional dependence of the laser spot, for which the result is near zero.

The experimental setup for EOC studies is described in depth elsewhere^v. Briefly, it consists of exposing degenerately doped GaAs to a focused laser spot. Equation (2) is then used to fit the measured $V_{12}(x_1, x_2)$. First x_1 and x_2 are fixed at the voltage lead positions corresponding to the experimental positions (3.4 mm and 6.6 mm). The voltage is then calculated using Eq. (2) with x and y limits of integration over a 40 μ m square, a length equal to the diameter of the laser spot. This voltage is then compared to the positional experimental data and σ_o is found, to establish the scale of the signal. Experimental data for $y = 0$ mm and a theoretical fit for $y = 0.1$ mm are shown in Fig. (1). This mismatch in y is further explained below. The discrepancy between experiment and theory from $x = 0$ mm to $x = 2$ mm is possibly due to the lead at $y = 0$ mm which, not being a point-like contact could disrupt the local electron-hole pairs generated in this corner region. The x -positional experimental data for the hybrid device shows excellent agreement with V_{12} considering that $\sigma(y)$ is independent of x and only the x -positional dependence is included.

We now address models for the charge density variation with y position. Figure (2) inset shows a plot of the $\sigma(y)$ models for both the bare and MSH structures.

A. Uniform Charge Density

The first way to model the surface charge created is to assume that the uniform illumination creates a uniform charge density, σ_o , but only where illumination occurs. The effect of the metal shunt is also incorporated via $\sigma(y)$. For the bare sample,

$$\sigma(y)_{bare} = \sigma_o \quad (3)$$

while, for the hybrid,

$$\sigma(y)_{MSH} = \sigma_o \left[1 + \frac{1}{2} \theta(y - y_s) \right]. \quad (4)$$

Here, θ is the step (Heaviside) function. The factor $1/2$ is derived from the fact that the proximity to the shunt increases the net positive charge as the more mobile electrons are taken to ground more effectively. The parameter y_s reflects the intrinsic differential mobility of the material of interest. A large (small) value of y_s would indicate that all (a limited number) of the mobile carriers have access to ground via the shunt. By integrating these charge densities over the entire illuminated area, the total net charge could be found. In this model, y_s is the distance away from $Y_{\max}$ over which it is assumed that the electrons are effectively shunted to ground.

This analytical model is limited because of its simplicity. Because of the first order pole that exists in Eq. (2) when $y = 0$ and $x = x_{1,2}$, when $\sigma(y)$ is constant, the voltage is very large. This was previously¹ attributed to experimental uncertainty in the definition of $y = 0$, but an additional reason may be the inaccuracy of the model at small y values near the voltage probes. When this model is used to fit experimental data as a function of y , $V_{12}(y)$, it does not fit well due to the $1/y$ nature of the position dependence.

B. Experimentally Fit Charge Density

One may also fit $\sigma(y)$ to experimental $V_{12}(y)$ data. The experimental voltage for a focused laser spot as a function of y -positional data as shown in Fig. (2) allows the fitting of V_{12} . Because the data, $V_{12}(y)$, is approximately Gaussian, the integrand in Eq. (2) must be of the form of $y \cdot \exp(-y^2)$. Taking in mind the $1/y$ positional dependence one can solve for $\sigma(y)_{bare}^{fit}$ and $\sigma(y)_{MSH}^{fit}$ and one finds

$$\sigma(y)_{bare}^{fit} = \sigma_o \frac{y}{y_m} e^{-\left(\frac{y-y_b}{r_b}\right)^2} \quad (5)$$

$$\sigma(y)_{MSH}^{fit} = \sigma_o \left[\frac{y}{y_m} + \left(\frac{y}{y_m}\right)^2 \right] e^{-\left(\frac{y-y_b}{r_b}\right)^2} \quad (6)$$

where σ_o is the charge density above. The effective radii of the Gaussian fits, $r_h = 1.5$ mm and $r_b = 0.3$ mm, illustrate the effect of the metal shunt in broadening the charge density. The offsets, $y_h = -0.88$ mm and $y_b = 0.14$ mm, are too large to be due to experimental positional uncertainties but the significance of this is not known. The last parameter, $y_m = 1$ mm, corresponds to the relevant length scale of the problem. The resulting $V_{12}(y)$ agrees very well with experimental Gaussian dependence of the voltage as shown in Fig. (2). The fact that the metal shunt is found to add a linear term to the surface charge density of the bare semiconductor, and that these terms are equal in magnitude, is very interesting. An explanation is to recall that although the charge density is being modeled as a positive point charge, there exists a more diffuse negative distribution of charge from the more mobile carriers. This linear term could be attributed to the ability of the metal to remove this negative distribution of mobile carriers, thus reducing the effect of the shielding.

This model is useful as it fits the experimental data precisely. While this model could be expected to fit various ratios of $X_{\max}/Y_{\max}$, experimental data exists for only one ratio. Thus the lead position to optimize the voltage and the EOC can only be computed for this ratio. This fit cannot be extrapolated to fit an arbitrary geometry. The weakness in experimentally fitting the voltage is in understanding why the apparent y -symmetry should be broken. For the hybrid sample, this lack of symmetry in the y -dependence is expected as the metal introduces an

asymmetry in y . But, for the bare sample one would not expect a focused beam to create more charge close to the leads as opposed to farther away from the leads as shown in the inset of Fig. (2)? A possible explanation for the non-uniformity of the surface charge as a function of y is that the leads at $y = 0$ break the y symmetry because, like the shunt, they can alter the charge distribution in their vicinity.

Results and Discussion

A. Uniform Charge Density, Role of Geometry

Using the constant charge density model, consider the role of the geometric ratio of $Y_{\max}$ to $X_{\max}$ of the device under uniform illumination. Because the total surface area is changing, there are two relevant cases. In the first case the **total** surface charge (equivalently laser power) is constant while in the second case the surface charge **density** (equivalently laser power density) is constant. First, the output voltage of the devices will be examined followed by a discussion of the EOC for these two cases.

For fixed **total** surface charge, $\sigma(y)_{\text{bare}}$ and $\sigma(y)_{\text{MSH}}$ are integrated over the entire surface of the device. Then, this total charge is conserved as the device area increases. The magnitude of V_{12} for both the bare and hybrid devices decreases with increasing $Y_{\max}$. Conversely, if the surface charge **density** is fixed, the signal increases for both devices plateauing near the ratio of $Y_{\max}/X_{\max} = 2$. This is shown in Fig. (3), which is a plot of the output voltage and EOC as a function of the ratio $Y_{\max}/X_{\max}$. At a ratio of 2 ($Y_{\max} = 20$ mm), the hybrid device signal has increased by 260% compared to when $Y_{\max} = 1$ mm. Here, unlike previous results^{i,v}, the maximum EOC does not correlate with the maximum voltage, V_{12} .

When $Y_{\max}$ increases, the EOC, as defined in Eq. (1), decreases monotonically both when the **total** surface charge and the surface charge **density** are fixed. As $Y_{\max}$ increases, charge conservation forces the surface charge density to decrease, distributing more charge density farther away from the voltage leads. This leads to a diminution of the effect of the shunt, thus decreasing the hybrid voltage. This effect is uniform, independent of the symmetry of the leads or of the illumination. If the surface charge **density** is held constant, the EOC starts at 50% but also decreases with $Y_{\max}$, asymptotically approaching zero as can be seen from Fig. 3. Physically, as $Y_{\max}$ increases, the distance to the charge density enhanced by the shunt also increases. Having explored $\sigma(y)_{\text{bare}}$ and $\sigma(y)_{\text{MSH}}$ in depth, consider now the effect of changing the lead positions when the ratio $Y_{\max}/X_{\max}$ is fixed at 1/10.

B. Uniform Illumination Over Half of the Sample with Symmetric Leads

To impose uniform illumination over half of the sample with constant surface charge density, $X_{\max}$ in Eq. (2) is replaced by $X_{\max}/2$. This equates to uniform illumination on the left half only; the right half being blocked or covered. With symmetric leads, Fig. 3 inset shows the EOC as a function of y_s . Because the voltage of the bare device is independent of y_s , the EOC trend follows that of the hybrid device, decreasing from a maximum of 50% to a minimum of zero. If the electrons over the whole area had access to the shunt ($y_s = 0$), the net effect would be a 3/2 increase in V_{12} , corresponding to an EOC of 50% (see Eq. (1)). When $y_s = Y_{\max}$, the shunt plays no role in the transport (see Eq. (4)) yielding the expected EOC of zero.

C. Asymmetric Lead Placement

For uniform charge density and fixed $y_s = 0.5$ mm, Fig. 4(a) represents the voltage output of the hybrid under uniform illumination with lead positions (x_1, x_2) displayed on the xy -plane and the voltage displayed on the ordinate. By plotting both lead positions over the full range the symmetry becomes apparent. This symmetry is due to the fact that $V_{12}(x_1, x_2) =$

$-V_{12}(x_2, x_1)$. In the xy -plane, where $x_1 = x_2$ (see Eq. (2)) or $x_1 = X_{\max} - x_2$, the EOC is undefined, as V_{12} for the bare device is exactly zero.

Because of the simplicity of the constant charge models $\sigma(y)_{bare}$ and $\sigma(y)_{MSH}$, the EOC, where defined, is found to be independent of the lead position (x_1, x_2) . This can be shown readily by substituting Eq. (2) directly into Eq. (1). Therefore, the optimal lead positions correspond to the maximum voltage, e.g. $(x_1, x_2) = (0, 5 \text{ mm})$ or $(10 \text{ mm}, 5 \text{ mm})$ displayed in Fig 4(a). These positions, with one lead in the middle and one at either end, can be understood qualitatively as the middle lead being closest to the most charge compared to the one on the edge that has access to the least.

Upon calculating V_{12} using the fit charge densities, $\sigma(y)_{bare}^{fit}$ and $\sigma(y)_{MSH}^{fit}$, the EOC is found to be dependent on the lead position. Figure 4(b) shows the general trends observed in the EOC. For each value of x_1 , the optimal lead placement to maximize the EOC was at $x_2 = 5 \text{ mm}$. However, for each value of x_1 , the optimal place for the voltage lead was at either end, $x_2 = (0, 10 \text{ mm})$. The maximum EOC of nearly 600% is achieved with $x_1 = 5 \text{ mm}$ and $x_2 = \sim 5 \text{ mm}$. This does not correspond with the maximum voltage and therefore EOC is not a useful gauge of a good sensor in this particular case.

D. Asymmetric Lead Placement and Uniform Illumination Over Half of the Sample

For the uniform charge density with $y_s = 0.5 \text{ mm}$, Fig. (4)(c) represents the voltage difference between the MSH and bare device under non-uniform illumination with lead positions displayed on the xy -plane and the voltage, V_{12} , on the ordinate. The symmetry when $x_1 = X_{\max} - x_2$ is lifted as evident in Fig. (4)(c) because the illumination is now asymmetric in x . Again, the EOC (not shown) is independent of lead position as discussed above. Therefore, the optimal lead placement is found at $(x_1, x_2) = (2.5 \text{ mm}, 10 \text{ mm})$, with one lead in the middle of the illuminated region and one on the far end of the non-illuminated region.

For the experimentally fit surface charge density models, the EOC is shown in Figure (4)(d). The lead position for the maximum EOC does not correlate with the lead position for the maximum signal. A maximum EOC of over 600% occurs at $(x_1, x_2) = (10 \text{ mm}, 10 \text{ mm})$ while the maximum voltage occurs at $(x_1, x_2) = (2.5 \text{ mm}, 10 \text{ mm})$.

Summary and Conclusions

Two methods are presented to break the net zero voltage effect due to the symmetry of uniform illumination in EOC structures. The first method is to impose uniform illumination on only half the sample. This method is limited by practical fabrication methods if the device dimensions are taken to the nanoscale. The second way is by introducing an asymmetry in the voltage lead placement. The surface charge density was modeled in the y direction in two ways; one with constant charge density and the other by fitting experimental data. Eq. (2) readily reproduces the x -dependence of the experimental data giving weight to the validity of the point charge model.

The EOC reaches a maximum of nearly 600% for $x_1 = 5 \text{ mm}$ and $x_2 = \sim 5 \text{ mm}$ using the fit surface charge density models. However, the voltage lead positions for maximum EOC were found to not correlate with the voltage lead positions for maximum voltage, making EOC a poor indicator of the suitability of the device as a sensor. Because EOC is only an indicator of the effect of the geometry, one must also consider the magnitude of V_{12} in sensor design. Ideally, the geometry is optimized as such to maximize the effect of the shunt, thus increase the signal.

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FIG 1.

The x dependence of the potential difference V_{12} (solid line) calculated from Eq. (2) of the text for $Y = 0.1\text{ mm}$ using the metal-semiconductor structure. Experimental data ($Y=0\text{ mm}$, $\blacklozenge$) were taken at 300 K with a power density of $6.3 \times 10^4\text{ W/cm}^2$. Insets show (a) a metal semiconductor hybrid device and (b) bare semiconductor device and relevant variables used in the model. The dashed line represents y_s from Eq. (4).

FIG 2.

The y dependence of the potential difference V_{12} (solid line) calculated from Eq. (2) of the text for $X = 3.4$ mm using the devices shown as insets in Fig. (1). Experimental data ($x = 3.4$ mm, $\blacklozenge$) were taken at 300 K with a power density of 6.3×10^4 W/cm². The inset shows the y dependence of the four surface charge densities used in Eq. (2). The legend is as follows: $\sigma(y)_{bare}$ (solid), $\sigma(y)_{MSH}$ (— —), $\sigma(y)_{MSH}^{fit}$ (— · —), and $\sigma(y)_{bare}^{fit}$ (- - -).

(y)_{bare} (solid), $\sigma(y)_{MSH}$ (— —), $\sigma(y)_{MSH}^{fit}$ (— · —), and $\sigma(y)_{bare}^{fit}$ (- - -).

FIG 3. V_{12} for the bare (---) and hybrid (— · —) sample and EOC (solid) as a function of the ratio $Y_{\max}/X_{\max}$ for $y_s = 0.5$ mm under uniform illumination but asymmetric lead placement. The inset shows the EOC as a function of y_s for $Y_{\max}/X_{\max} = 1/10$ for asymmetric illumination but symmetric lead placement.

FIG 4.

The lead position dependence of the potential difference V_{12} calculated from Eq. (2) of the text for the MSHs shown in Fig. (1). (a) The device has uniform illumination over its full surface with lead positions (x_1 , x_2) displayed on the xy -plane and the voltage displayed on the ordinate. (b) The resulting EOC calculated using Eqn. (5) for the bare semiconductor and Eqn. (6) for the hybrid structure. (c) The lead position dependence of the potential difference V_{12} for a device that has uniform illumination only over half of its surface. (d) The resulting EOC. The break at $x_1=x_2$ is an artifact where the bare device voltage goes through zero.