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Note: Fiber optic transport probe for Hall measurements under light and magnetic field at low temperatures: Case study of a two dimensional electron gas

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A fiber optic based probe is designed and developed for electrical transport measurements in presence of quasi-monochromatic (360–800 nm) light, varying temperature (T = 1.8–300 K), and magnetic field (B = 0–7 T). The probe is tested for the resistivity and Hall measurements performed on a $LaAlO_3$–$SrTiO_3$ heterointerface system with a conducting two dimensional electron gas. © *2015 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4921486]

The properties of material may change by exposure to light due to modification in their carrier density, degree of interaction between spins, or electronic structure. Illumination with light has led to a spectrum of new phenomena, like persistent photoconductivity, insulator-to-metal transition, introduction/enhancement in superconductivity, destruction of charge ordered state, and photo-induced magnetic disordered phases.[1–5] Recently, heterointerfaces of the wide band gap insulating oxides $SrTiO_3$ (STO) and $LaAlO_3$ (LAO), exhibiting the formation of conducting two dimensional electron gas (2DEG), have been a focus of research worldwide.[6–8] A photo-induced response study of these heterointerfaces has been important to explore the underlying mechanism and optoelectronic effects in 2DEG.[9–13] Naturally, it is important to supplement these studies with measurements of photo-induced carrier concentration changes.

There is no dearth of standard transport probes (STP), using variable temperature cryostats with superconducting magnets, capable of resistivity and Hall measurements. The novelty of the present work lies in a simple design and development of a fiber optic transport probe (FOTP) that simultaneously couples light in a controlled fashion onto a sample placed in a cryogenic environment under high magnetic field. LAO-STO with an active 2DEG, as test sample, demonstrates the potential of FOTP. The observed changes in photo-induced carrier density suggest a change in the spatial confinement of 2DEG in the studied system.

The setup can be mainly divided into two parts: the cryostat and FOTP. The former is constituted by variable T (1.8–400 K) and B (0–7 T) cryostat (Quantum Design MPMS). The FOTP part is designed and built in-house. The design part of the SMA (Sub-Miniature version A) terminated quartz optical fiber at one end of the probe (SS tube with length ~1.5 m and id ~3 mm) and the slide seal assembly is similar to that in Ref. 14. The same end also has a vacuum tight micro-connector terminated with 2 quads of phosphor bronze wires coming from the sample end for electrical transport measurements. The schematic of the sample holder is shown in Fig. 1(a). The sample mount, which can hold samples with size up to 5×5 mm^2, can also be moved up/down with respect to the fiber end. For the used large cross section (diameter ~1.4 mm) multimode fiber with ~3 m length between the sample end and light source, the illuminated area is expected to be fairly uniform. A light source based on Xenon lamp (LOT-Quantum Design) was used to produce, depending on the filter, quasi-monochromatic (FWHM ~40 nm) light of various wavelengths lying in a range of 360–800 nm.

A LAO-STO thin film (3×3 mm^2) prepared by pulsed laser deposition technique was employed as a test sample. The film was mounted at a distance of ~4 mm from the fiber end. Gold wires were indium soldered to four thermally evaporated pads (~1 mm^2) in Van der Pauw geometry for resistance and Hall measurements.

The FOTP was first tested for temperature accuracy in dark. Resistance (R) versus temperature measured on a superconducting NbN film using both the FOTP and a calibrated STP is shown in Fig. 1(b). Both the probes are in excellent agreement over the entire T-range. Second, the fluence (F) of the incident photons was calibrated against the aperture of the light source. The change in fluence measured at the sample end as a function of % aperture opening is shown in the inset (b1) of Fig. 1(b) for two wavelengths 405 and 800 nm. The fluence saturates for more than 30% aperture opening for both the wavelengths with saturated values $\sim 5 \times 10^{13}$ and 3×10^{14} (photons/s)/cm^2, respectively. All the data in this work belong to the saturation region with 100% aperture opening. A calibrated Cernox sensor (CX-SD, Lakeshore) was used as a sample to get an idea of possible light induced heating effects in the FOTP. The inset (b2) of Fig. 1(b) shows the light induced rise in T (ΔT) of Cernox sensors, estimated from the change in resistance under illumination, versus its temperature in dark. As seen in the inset, $\Delta T \sim 0.46$ K (0.07 K) and 0.32 K (0.05 K) at 2 K (9.5 K) for 405 and 800 nm, respectively. The rise in T can be reduced by lowering the power of the incident light.

Now we show the effect of light on the transport properties of LAO-STO heterointerface studied using FOTP. The dark resistance R_d of the sample decreased from 2160 Ω (549 Ω) to a 405 nm light induced value ~2012 Ω (388 Ω) at 300 K (10 K), indicating a strong influence of light on the conductivity of the heterointerface. The percent change in photo-induced resistance $R_{PI}[= (R_d - R)/R_d]$ versus time, at 10 and 300 K, is shown in Figs. 2(a) and 2(b), respectively. Note that

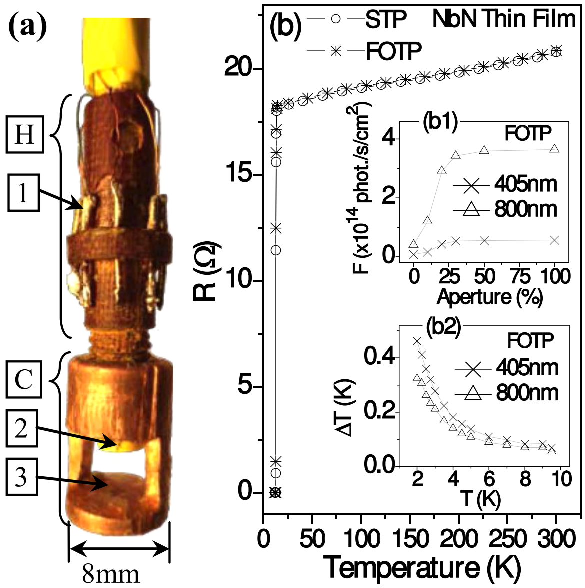

FIG. 1. (a) Schematic of the sample holder: H-Hylum part—1. electrical connections; C-Copper part—2. optical fiber and 3. sample mount. (b) R versus T of a superconducting NbN thin film measured by FOTP and a calibrated STP. Insets: (b1) Incident light power at the sample end as a function of % aperture opening and (b2) temperature rise (ΔT) of a Cernox sensor under light as a function of its temperature in dark.

$R_d = R(t = 0)$. The influence of light was measured at two different wavelengths 405 nm (3.06 eV) and 800 nm (1.55 eV). At both the temperatures and wavelengths, switching the light "on" ("off") results in a sharp increase (decrease) in $R_{PI}(t)$, followed by a faster (much slower) evolution of flatter region. However, at higher T and wavelength, the response is found to be significantly suppressed. Similar T dependence has been reported previously.[11,12] The observed increase in R_{PI} (at t = 0) with increasing light energy (1.55–3.06 eV) is also in agreement with earlier reports,[13] where finite absorption by in-gap states in STO band gap was responsible for such a behavior. As seen further from Figs. 2(a) and 2(b), in comparison to 300 K, switching the 405 nm light "off" at 10 K does not recover $R_{PI}(t)$ to its dark value. In other words, at 10 K, the illumination of the LAO-STO heterointerface has resulted in a quasi-permanent change in the R_d. These results

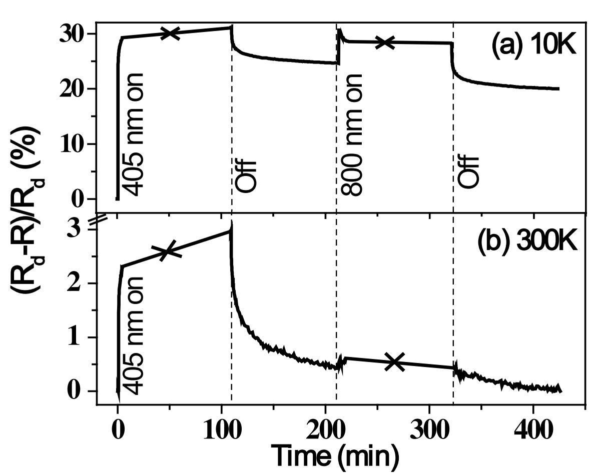

FIG. 2. $(R_d - R)/R_d$ versus time of LAO-STO sample with light switched "on" and "off" at (a) 10 K and (b) 300 K.

indicate that photo-induced electron-hole pair recombination is a thermally activated process, which diminishes at lower temperatures due to lowering of available activation energy (see Refs. 9 and 11 also). Note that, subsequently switching the 800 nm light "on" and "off" does not influence the trajectory of $R_{PI}(t)$ recovery (see Fig. 2).

The observed changes in 2DEG resistance by light illumination in general suggest a change in the electronic density at the LAO-STO heterointerface, which can be measured using FOTP. The Hall measurements, as marked by "X" in Figures 2(a) and 2(b), were simultaneously performed in Van der Pauw geometry while measuring $R_{PI}(t)$. At both 10 and 300 K, Hall resistance H_R (= V_H/I, where I is the current and V_H is the Hall voltage) was measured as a function of magnetic field in "on" and "off" condition for 405, 605, and 800 nm light. As representative Hall curves, we show $H_R(B)$ plots measured in dark at 300 and 10 K in Fig. 3(a). The sheet carrier density (n_s) is directly calculated from the slope (= $(1/n_s e)$) of the H_R (B) plots. All the measurements were carried out three times and the mean values as a function of wavelength are shown in Fig. 3(b). The value of n_s ($\sim 3.4 \pm 0.10 \times 10^{14}$ cm^{-2}) in dark at 300 K matches very well with the value ($\sim 3.3 \times 10^{14}$ cm^{-2}) suggested by polar discontinuity of 1/2 electron per unit cell at the interface.[15] The observed decrease of n_s in dark with decrease in T is in agreement with previous reports.[16,17] At both 10 and 300 K, within the error, both by illumination and decreasing the light wavelength, a slight decrease in n_s of the sample can be delineated (see Fig. 3(a)). Note that in this comparative study, a small variation in intensity across the sample would not affect our conclusions as long as the sample is placed at the same location for measurement at each wavelength.

The variation in n_s with light wavelength cannot be uniquely correlated because of different incident power for different wavelengths. However, with respect to dark, the simultaneous increase of conductance and decrease in the value of n_s under illumination, at all the tried wavelengths,

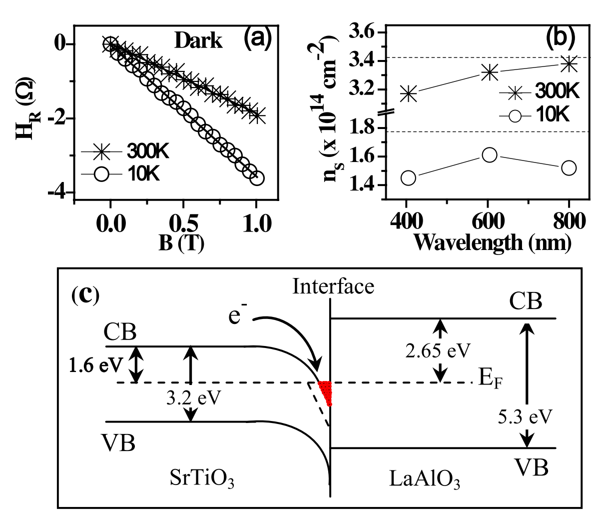

FIG. 3. (a) Hall resistance versus magnetic field at 300 and 10 K in dark. (b) Sheet carrier density as a function of wavelength at 300 and 10 K. The dashed horizontal lines represent the respective dark values. (c) Simplified band diagram of LAO-STO showing the potential well in dark (solid triangle) and modified under light (dashed triangle).

are counter-intuitive. Below, we try to understand this contradiction with the help of simple modification in the band diagram of LAO-STO heterointerface under light.

The conductivity of LAO-STO system in dark arises by the formation of 2DEG at the heterointerface that can be represented by an electron pile-up in the potential well at the interface (Fig. 3(c)). Upon illumination, electron-hole pairs are generated in the STO substrate. The photo-generated electrons in the conduction band of STO presumably migrate to the interface potential well and increase the number of electrons in the 2DEG, as demonstrated by the change in $R_{PI}(t)$. To compensate this photo-induced change in the potential at the heterointerface, the separated holes get trapped in the substrate and/or at the surface, as is evident from the observed slower recombination dynamics in the light "off" state. Now the increased number of electrons at the heterointerface can influence the potential well in two ways; it may increase either its depth (i.e., n_s increases) and/or its width (i.e., n_s stays unchanged). Our results favor the latter case where thickening of the 2DEG in the presence of light can be envisioned. In such a scenario, the increase in $R_{PI}(t)$ can be simply attributed to the increased current carrying cross section area. We need to mention that in Ref. 13, the photo-induced change in the resistance for light energy greater than the STO band-gap has been attributed to a transfer of photoexcited carrier to a sub-band where the carrier mobility is high; this two-band picture enables Guduru *et al.*[13] to explain the non-linear Hall data.

A fiber optic transport probe capable of electrical transport measurements in a range of T = 1.8–300 K, B = 0–7 T (or higher), and light wavelengths between near UV to near IR has been designed, developed, and tested. Good temperature stability and minimal heating effects were achieved under light illumination. The probe was used to investigate the light induced transport properties of a 2DEG formed at LAO-STO heterointerface. The combined change in measured photo-induced resistance and the carrier concentration suggests an increase in the effective thickness of the 2DEG at the heterointerface.

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