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Novel optical probe for quantum Hall system

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Abstract. Surface photovoltage (SPV) spectroscopy has been used for the first time to explore Landau levels of a two-dimensional electron gas (2DEG) in modulation doped InP/InGaAs/InP QW in the quantum Hall regime. The technique gives spectroscopically distinct signals from the bulk Landau levels and the edge states. Evolution of the bulk Landau levels and the edge electronic states is investigated at 2.0 K for magnetic field up to 8 T using SPV spectroscopy.

Keywords. Surface photovoltage spectroscopy; quantum Hall effect; Landau levels; edge states.

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1. Introduction

Integer quantum Hall effect (QHE) arises from quantization of energy of two-dimensional electron gas (2DEG) under perpendicular magnetic field. QHE is characterized by exact quantization of Hall resistance $R_{\mathrm{H}} = h/ve^2$ at magnetic field values where integral number $\nu = n/(eB/h)$ of Landau levels are completely filled, where n is the two-dimensional (2-D) electron density, B is the magnetic field, e is the electronic charge and h is the Planck's constant. It is known that robustness of this effect, i.e. value of the Hall resistance at plateaus is constant to precision of few parts in 10 million [1] independent of the sample details such as material system and purity etc., is connected to dissipationless current flow in the plateau regions along the edges of the Hall bar sample in the electronic states called 'edge states' [2–4]. Because of their considerable significance, a variety of experimental techniques have been used to investigate the edge states. These include (a) Hall voltage distribution across the sample width [5], (b) capacitance of edges [6,7], (c) time-of-flight along the edges [8], (d) tunneling into edge states [9], and (e) photovoltage generated by excitation of electrons from filled Landau levels to empty Landau levels within the conduction band [10]. While these studies have given insight about compressible/incompressible stripe regions, total width of the edge region and fraction of current carried by the edge states vs. the bulk states, there has been no direct spectroscopic measurement of the edge states comparable to the measurement of absorption or photoluminescence from bulk Landau states. Transmission measurements in the bulk generally involve multiple quantum wells. On the other hand, the PL measurements give information about the lowest energy transitions. Performing absorption measurements on edge states located at the sample boundaries of a single quantum well sample appears a very challenging task. In the recent years, surface photovoltage spectroscopy has been applied increasingly to study electronic transistions involving nanostructures where the sample volume is very small [11]. Thus it appears to be a technique suitable for studying the edge states. It may appear that in order to selectively excite the states located at the sample boundary, one would have to use a scanning probe method. However, by using surface photovoltage spectroscopy, we show that signals from the bulk and the edge regions are spectroscopically distinct such that we can probe the edge states distinctly from the bulk Landau states even with uniform illumination of the sample.

2. Experiment

In a SPV experiment, electron–hole pairs are generated near the surface of a semiconductor when light of appropriate wavelength irradiates the sample. Crucial to the experiment, the electron–hole pairs are then separated by the internal fields which usually exist in the surface region of the semiconductor. Separation of electrons and holes produces a change in the surface potential which can be picked by an electrode in contact with the surface. Thus, the surface photovoltage signal shows a step when the incident photon energy crosses the bandgap energy. In case the sample has a quantum well structure, the signal shows steps at various wavelengths with each step corresponding to the onset of transition between higherlying electronic levels in the QW. Generally therefore, the SPV spectrum is generated by excitations between electronic energy levels of the semiconductor as much as in an absorption spectrum. In the present experiment [12], the sample consists of 2DEG in a QW of InGaAs, produced by modulation doping from an adjoining layer of doped InP. The 2-D electron density in the well is $6\times10^{11}/\mathrm{cm}^2$. The sample is kept in a cryogenic vessel where the sample temperature can be lowered to 1.5 K. The sample is positioned in the middle of a superconducting solenoid magnet (magnetic field variable from 0–8 T), such that the magnetic field is perpendicular to the plane of the 2DEG. An optical fibre carries light from tunable diode laser source covering a range of photon energies between 763–816 meV (figure 1). Equivalently, a multimode fibre with lamp and monochromator combination can be used for wider range of wavelengths.

For measuring the SPV spectrum an ohmic contact to the sample (2DEG in the QW) forms one electrode and an indium tin oxide (ITO)-coated semi-transparent glassplate pressed softly on the sample surface forms the second electrode as shown schematically in figure 2. The ITO-coated glass has transmission of about 10% in the wavelength range 1520–1625 nm used in the present experiments. As shown, the ITO electrode measures the bulk SPV spectrum corresponding to the interior of the QW. In order to make arrangement for the SPV signal from the edge of the QW, the sample is first covered with positive photoresist and a fresh edge is cleaved.

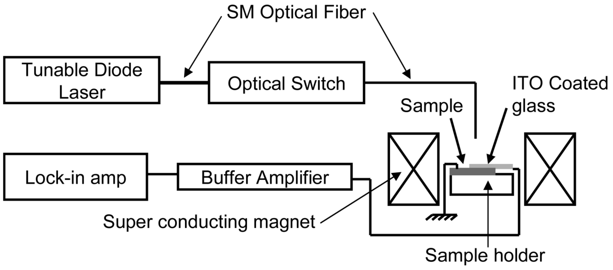

Figure 1. Schematic experimental setup for SPV measurement.

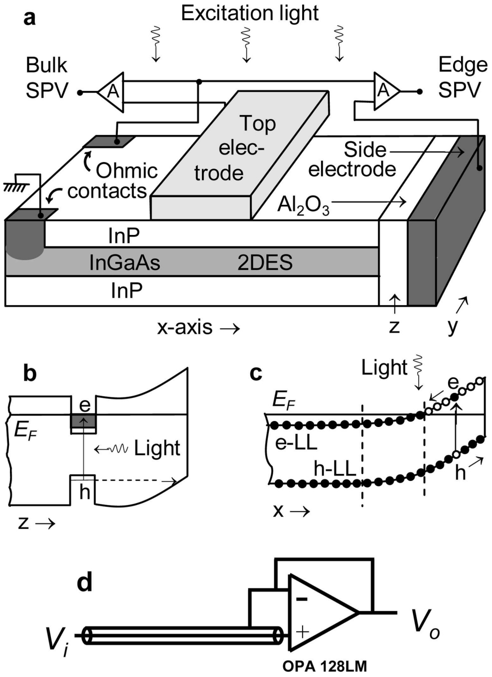

Figure 2. (**a**) Schematic device structure and measurement setup. The side electrode is made by e-beam evaporation of 25 Å Al_2O_3 and 1000 Å gold on the (1 1 0) cleaved surface. Top electrode is a conducting indium–tin-oxide coated glass in soft contact with the top of the sample. 'A' is unity gain buffer-amplifier circuit made of electrometer-grade operational amplifiers. (**b**) Schematic band diagram along the growth direction (z) to explain B-SPV signal generation. (**c**) Schematic band diagram along the plane of the QW(x) towards the boundary to explain E-SPV signal generation. Electron and heavy hole Landau levels are labeled e-LL and h-LL respectively. Vertical dashed lines separate bulk-region, conducting strip and depletion strip successively. (**d**) Buffer amplifier is made to measure SPV signal generated from sub-femto Coulomb charge variation.

This is followed by deposition of 25 Å layer of Al_2O_3 for isolation and 1000 Å layer of Au for the side contact. Very sensitive unity gain buffer amplifier circuit made of electrometer grade operational amplifier is used to measure the edge SPV signal. The shield of the input cable is driven by the output of the amplifier to nullify the cable capacitance. Very low input bias current ($\sim$40 fA), low offset voltage ($\leq$100 μV) and low input capacitance of the buffer ($\sim$1.6 pF) enable the circuit to measure the photovoltage generated from subfemto Coulomb charge change at the surface as a result of optical excitation. Differential voltage is measured between two such amplifiers, one connected to ohmic contact and the other to either the top ITO electrode (for bulk SPV or B-SPV) or to the side Au electrode (for edge SPV or E-SPV).

The device used for the SPV experiment, shown schematically in figure 2, is made from sample of 5 mm × 5 mm size. Two ohmic contacts Au–Ge are alloyed as shown. Silver paint is used to attach a gold wire to the side electrode. For the B-SPV measurements, the incident light intensity is $\sim$10 μW/cm^2, which reduces to $\sim$1 μW/cm^2 after passing through the ITO. The light intensity used for the E-SPV experiment is about 30 nW/cm^2. The photogenerated signal is measured with lock-in amplifier. The experiments are done at temperatures 1.5–2.0 K in a super insulated cryostat. Light is chopped using a MEMS optical switch triggered with lock-in amplifier.

3. Results and discussion

The B-SPV and E-SPV spectra measured at zero magnetic field are compared in figure 3. The edge spectrum rises abruptly at an energy characteristic of the band edge of the QW with no excitonic-like feature and is flat at higher energies. The B-SPV spectrum on the other hand is shifted to higher energy in comparison to the E-SPV spectrum. This is a very crucial result and shows that signal from the edge states is distinguishable from signal from the bulk states. Blue-shift of the B-SPV spectrum compared to the E-SPV spectrum results from band filling by the 2DEG as these transitions occur from the filled valence band states to empty conduction band states lying above the Fermi energy E_{F} in the QW. At the edge, the electron density goes to zero in the conduction band and the light is absorbed for $h\nu \geq Eg$, whereas in the bulk, the absorption occurs at energy $h\nu \geq Eg + E_{\mathrm{F}}$. The comparison proves that the E-SPV experiment probes the edge states distinctively from the electronic states away from the edges in the bulk, without the need to restrict spatially where the light irradiates the sample.

The E-SPV spectra at selected B values are plotted in figure 4. The E-SPV spectrum for $B = 0$ rises abruptly at energy characteristic of the band edge of the QW as shown in figure 3. In the quantum Hall regime at high magnetic fields, distinct peaks in the E-SPV spectra evolve and shift to higher energy with increasing B. However, Zeeman splitting is not resolved indicating that the Zeeman energy is less than the broadening of the peaks. The peaks in the E-SPV spectra correspond to the transition energies between heavy hole edge states in the valence band to electronic edge states in the conduction band. By differentiating the $B = 0$ curve numerically, we obtain the band gap energy of the QW from the maximum of the

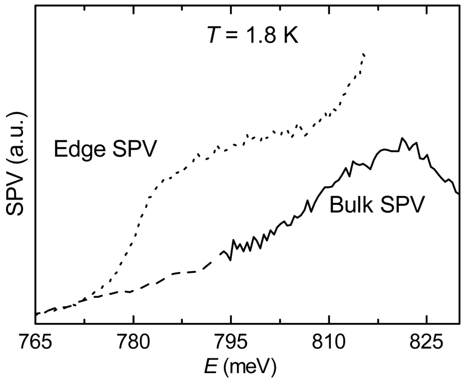

Figure 3. Comparison of the edge-SPV and the bulk-SPV spectra at zero B. At higher energies (792–830 meV), the B-SPV signal is measured by the conventional method at 8 K.

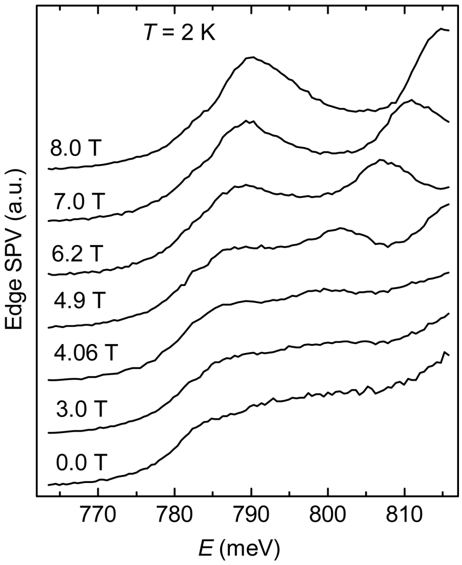

Figure 4. Plots of the edge spectra at different B fields (measured without passing any external current). The plots are shifted vertically for clarity.

derivative, as shown in figure 5a, $Eg = 780.9 \pm 0.3$ meV. To determine the edge transition energies at various magnetic fields, half-Lorenzian curves are fitted to the measured spectra after smoothing as shown in figure 5b. Half-Lorenzian curve fitting is used since the line shapes are not symmetric. The edge transition energies E_{T1} and E_{T0} obtained from the fitting procedure are plotted in figure 6 with varying B. A linear B dependence of E_{T1} and E_{T0} with respect to B is seen. We see that at $B = 0$ the E_{T1} and E_{T0} curves cross at ~781 meV, close to the bandgap energy determined from the $B = 0$ spectrum (figure 5a). The significance of these results will be discussed in detail in a forthcoming publication [13].

Returning to the measurement of the bulk SPV spectrum, we were able to make measurements over a limited range of wavelengths due to limitations of the available tunable diode laser source. Figure 7 shows the spectra at two B fields. The clearly resolved peak at energy 813.6±0.6 meV indicates the position of the Fermi energy in the bulk and matches with the energy $Eg+3/2(\hbar\omega_{\mathrm{r}})$, where $\omega_{\mathrm{r}} = eB\left(\frac{1}{m_{\mathrm{e}}^*} + \frac{1}{m_{\mathrm{h}}^*}\right)$ at 6.79 T. The hump at 793 meV does not change with B and its origin is not known. While a detailed spectral investigation of the B-SPV using lamp and monochromator arrangement is planned in the near future, B-SPV measurement performed at a fixed photon energy $h\nu = 815.8$ meV with varying magnetic field is shown in figure 8. This B-SPV signal is measured by keeping the sample edges covered with Al foil. At low field, we see oscillations in the B-SPV signal (inset of figure 8) analogous to the Shubnikov–de-Haas oscillations usually observed with magneto-resistance measurements. At high magnetic fields in the QH regime, sharp peaks appear in the

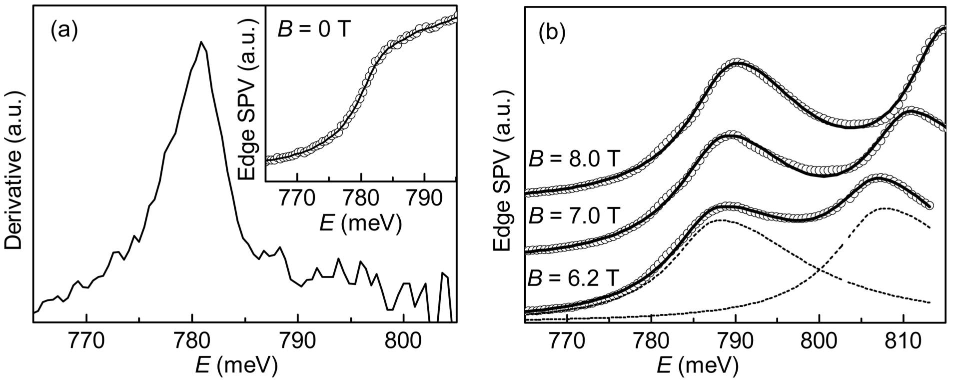

Figure 5. (**a**) Derivative of the smoothed edge SPV ($B = 0$) spectrum. Inset shows the edge SPV ($B = 0$) spectrum at 2 K. Hollow circular points are real data and the solid line is the numerically smoothed curve. (**b**) Curves fitted to the edge SPV spectra. Hollow circular points represent the numerically smoothed edge SPV spectra and the black solid lines are the fitted curves. Dotted lines are two components of the fitted curve for $B = 6.2$ T spectrum.

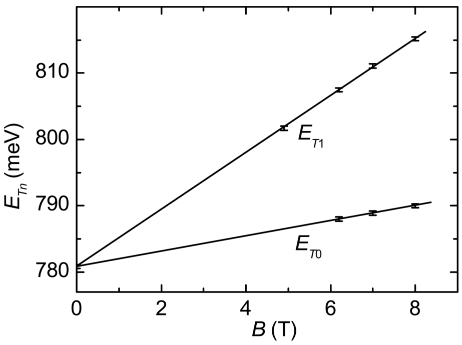

Figure 6. Plots of the transition energies E_{T1} and E_{T0} with B.

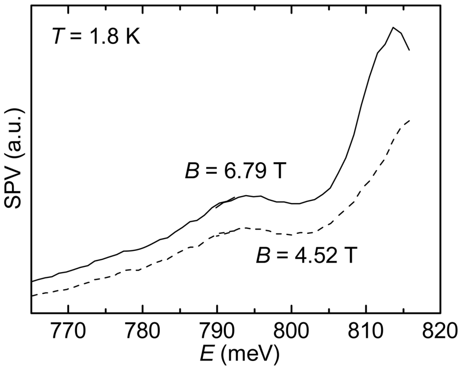

Figure 7. Bulk SPV spectra at $B = 6.79$ and 4.52 T corresponding to $n = 1$ and 2 respectively. The hump at 793 meV does not change with B and the origin of the hump is unknown.

B-SPV signal which correspond to plateau-to-plateau transistions. To enumerate the plateau numbers we have used a two-terminal magneto-resistance trace, shown along with the B-SPV plot in figure 8. Looking at the two plots together, we see that B-SPV peaks are seen only for the spin split Landau levels with even ν to odd ν plateau transitions and no peaks are observed for odd ν to even ν plateau transitions. As a conjecture, we feel that in order to observe the B-SPV peaks corresponding to the even ν to odd ν plateau transitions, a higher photon energy is necessary than available from our present set up. This experiment is currently planned using lamp and monochromater combination. Furthermore, it would be

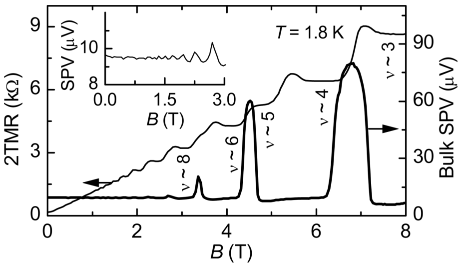

Figure 8. Plot of bulk SPV signal and 2 TMR with B. Inset shows the bulk SPV oscillations at low B.

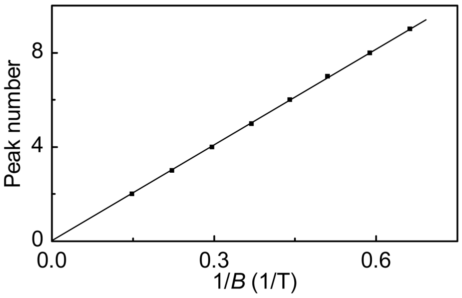

Figure 9. Plot of B-SPV peak number versus $1/B$.

desirable to use circularly polarized light to distinguish the transitions corresponding to the Zeeman spin split energy levels.

The oscillatory nature of the B-SPV can be used to estimate the electron density in the QW. For this, successive B-SPV peaks are assigned integer numbers in increasing order from higher to lower B fields and the B value corresponding to each peak is determined. Figure 9 shows plot of peak number versus $1/B$. The plot is linear and following the SdH oscillation analysis, the slope should be $n_{\mathrm{s}}h/2e$, which gives estimate of the 2-D electron density $n_{\mathrm{s}} = (6.60 \pm 0.03) \times 10^{11}/\mathrm{cm}^2$, close to the value determined from magneto-transport measurement.

Finally, we comment briefly on the B-SPV signal of figure 8. The strength of successive peaks increases with increasing B. At low B values, the separation between Landau levels eB/m^* is small and the density of states in each Landau level eB/h is also small. The number of filled Landau levels is $n_{\mathrm{s}}/(eB/h)$. This number reduces as the B field increases. Each peak in figure 8 indicates a Landau level crossing the Fermi energy. Increase in the strength of the successive peaks is thus due to increase in the density of states of the levels crossing E_{F} at higher B fields. We also see increase in the widths of the B-SPV signals. The shapes of the peaks are unusual – rising and falling rather sharply. Since the disorder in the sample broadens the Landau levels, with the centre of the level consisting of extended states surrounded by localized states which are sharply separated by mobility edges, it is possible that the observed line shape is a convolution of the transition probability and the density of extended states. This aspect is also being explored further.

4. Conclusion

A novel technique has been used to measure spectroscopically distinct signals from the bulk Landau levels and the edge states of a QW sample in the quantum Hall regime. Several new results have been obtained which require further experimental and theoretical investigations. The technique has potential for exploring other nanodimensional systems such as Luttinger liquid in fractional quantum Hall system.

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