New experimental approach on charging technique of helium surface over rectangular electrodes at cryogenic temperature

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We report results on the charging technique of liquid helium surface over rectangular electrodes and maximum sustainable electron density at temperatures above 1 K. Also, thermally activated escape of two-dimensional electrons from the potential well has been studied as a function of various parameters like electrons density and temperature. Results provide insights into the charging process of the surface-state electrons and their stability parameters over these electrodes with AC capacitive coupling technique.

Keywords: Cryogenics, capacitance measurement, printed circuits, thin films.

STUDY of surface-state electrons on cryogenic substrates has been of great interest in low temperature physics since the early 20th century. Their existence was conceived as early as 1939 and demonstrated both experimentally[1] and theoretically[2,3]. Cole *et al.*[2,3] suggested that surface state electrons above a liquid helium surface form a classical two-dimensional (2D) Coulomb gas at low areal densities. Hence, liquid helium can sustain a 2D electron gas on its surface states that is quantized perpendicular to the surface. The system shows the highest mobility ever known in condensed matter physics; electrons also display properties of liquids and solid crystals via inter-electron Coulomb interactions. In the bulk helium experiments, 2D electron densities are low[4], usually in the range 10^9–10^{13} m^{-2}. Higher densities cannot be realized as an electro-hydrodynamic instability of the charged surface occurs, which causes electrons to puncture through the liquid[5].

At first, an escape process was theoretically treated by Crandall[6,7]. According to Crandall, the escape rate is expected to reflect the inter-electron correlation in the 2D system, since the electrons escaping from the surface state into free space substantially changes depending on whether they are in a gaseous or crystalline state. In this context, an attempt to explain the escape of electrons from the saturated helium surface at low charging temperature within the thermal activation model was made by some researchers[8–10]. During the early development of study in this field, lifetime measurement was attempted by Willium *et al.*[8] who reported a lifetime of the order of 10^{-4} sec. They measured a strong dependence of the escape rate, which suggested that the surface electron system is in a liquid state. Later, a more detailed study was done by Iye *et al.*[9]. They studied the rate at which electrons escape from the 2D state into free space by thermal agitation. Andrei *et al.*[10] reported the first observation of tunnelling of electrons confined to a 2D layer through a barrier formed above the liquid helium surface. However, such experiments are difficult at high temperatures because the density of He-gas atom is very high leading to more frequent scattering between the path of the escaping electrons and gas atoms. Once the escaping electrons jump to the higher energy continuum state, they could return to the lower state by secondary scattering with gas atoms.

There is no experimental information available for the stability of electron density against minimum helium thickness over rectangular electrode arrangement. Here, we report on the charging technique and stability of charged helium surface, and electrons escaping from surface states to the three-dimensional free space over the electrode arrangement.

The aim of this communication is twofold. First, we describe the technique to charge the helium surface so as to incorporate those varieties of experimental conditions of stability of charged surface in a precise way. Second, we describe a general framework for the treatment of emission of electrons under the influence of positive extracting voltage pulse, $V_{\text{top-plate}}$, through the electrostatic potential barrier. We first discuss the experimental method followed by the results, discussion of the results and concluding remarks.

Electrical transport parameters of electrons were determined with AC-capacitive coupling technique using three ractangular electrodes. This technique is designed for the measurement of emission of electrons as well as surface resistivity of 2D electrons supported by the cryogenic fluid substrate. In the present experimental set-up, we have employed one electrode above the surface and three electrodes below it. These electrodes provide a vertical holding field for the electron gas. A sign wave was applied to one of the outer submerged electrodes and an induced signal on the other outer electrode was detected. The two electrodes were coupled via surface charge density. The third electrode was placed between them that reduced crosstalk between driving and pickup electrodes. The electrodes were mounted inside a copper circular symmetrical cell made of length 6.1 cm and diameter 5.7 cm. The electrodes were etched on a double-sided copper-clad epoxy board. The surface area of the electrodes was 1 cm^2.

The separation, D, between top and bottom electrodes was 6.5 mm. The maximum liquid helium thickness, d_{LHe}, was 1 mm. So the measurements presented here are

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observed only with the configuration d_{LHe} much lower than D, i.e. $d_{\mathrm{LHe}} \ll D$. The electronic circuit diagram for the experimental arrangement is shown in Figure 1. The coupling circuit consists of three resistors and three capacitors connected to a voltage source which sets the electrodes on a positive offset DC voltage. An AC voltage excitation V_{in} of a lock-in amplifier was superimposed on V_{dc}. Before loading the electrons over the helium surface, a positive potential $V_{\mathrm{dc}} = 3$ to 12 V was applied to all three bottom electrodes that pulled the electrons close to the liquid helium surface. The guard voltage was between –2 and –8 V to control the electron density at the helium surface during the experiments. Afterward, the lock-in signal of amplitude and phase were recorded. The recorded background amplitude (before loading electrons over helium surface) was 60 nV and phase was set to 0°. The top electrode was kept at ground during all measurements. Then the surface was charged up to saturation by applying some short pulses through the glassless filament. The electrons come to the surface until the electric field F_{vapour} above the electron layer becomes zero. The signal was increased in steps as a function of number of pulses applied.

A short voltage pulse applied to the top plate for a period of 10 min down to 500 ns caused the escape of electrons from the surface. The surface was charged up to saturation after each top plate pulse. Surface charge density was calculated before and after imposing each extracting voltage pulse through recorded amplitude and phase signals which were measured by a lock-in amplifier. Amplitude and phase were calibrated for different holding voltages and L^{4}He thicknesses above rectangular electrodes. Measurements were also done at different temperatures. The saturated electron density was determined using the following equation

$$n = \frac{\varepsilon V_{\mathrm{dc}}}{4\pi e d}, \tag{1}$$

where the dielectric constant $\varepsilon = 1.0576 \pm 0.006$ for liquid helium below 2 K, V_{dc} the voltage applied to bottom electrodes, e the electronic charge and d is liquid helium thickness.

A RuO_2 resistor was used as a thermometer which was calibrated using ^{4}He vapour pressure to measure the electron temperature. The thermometer was mounted on the cell. All the measurements were made in the temperature range between 1.59 and 1.95 K. It was assumed that there is no force acting on the electrons parallel to the liquid helium surface. Hence, the electron layer above the helium surface acts as a sheet of conducting metal. The experimental results are explained below.

Our study highlights the charging technique and stability of charged helium surface (i.e. stable signal at minimum liquid helium thickness over the electrodes). We have achieved maximum electron density $n_e \leq 2 \times 10^8$ electrons/cm^2 in our experimental system. We also included measurements like thermally activated escape of electrons from the helium surface over the potential barrier under the influence of applied external fields. This method is tried out by imposing a positive extracting voltage to the top-plate for a variety of pulse durations. Influence of pulses on escaping electrons was also observed.

We now explain measurement of the stability of fully charged helium surfaces. In the initial stage, several preliminary experiments were done using various techniques in order to achieve stable charge density over liquid helium surface. In this way, it was observed that electrons are pulled towards the surface under the influence of holding potential, but above bare electrodes it is not possible to keep a stable signal for long time. For this, the bulk liquid helium thickness should be higher than the gap of the electrodes, as shown in Figure 2. Only then the charged surface will be stable for long duration. This could be because the potential barrier decreases as the liquid helium level is far from the bottom electrodes and

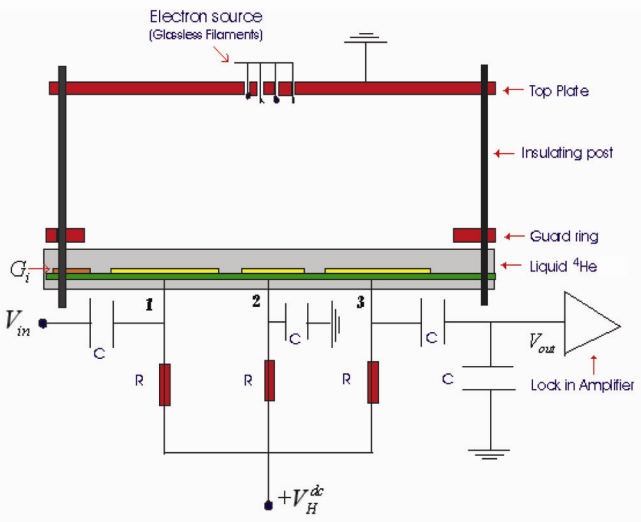

Figure 1. Electronic circuit diagram used for the measurement of escape of electrons over liquid helium surface is shown.

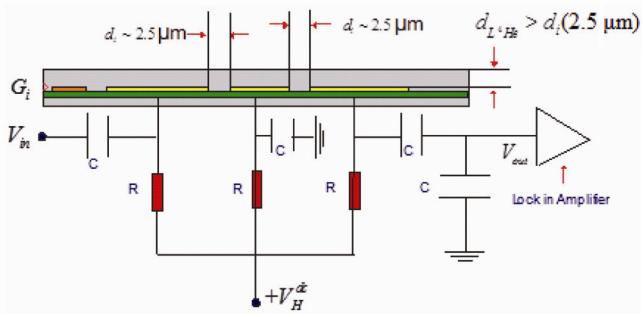

Figure 2. Observation of stable signal at minimum liquid helium thickness over bare electrodes.

potential barrier increases when the liquid helium level is placed closer to the electrodes. The liquid thickness determines the strength of interaction between an electron and its image charge. It affects the potential binding of electrons to the surface, and hence results in instability. In order to avoid such instability, liquid helium thickness must be higher than the gap between the bottom electrodes.

As the desired liquid helium thickness is obtained above the bottom electrodes, electrons are generated on the helium surface by means of thermionic emission. In order to charge bulk helium surface, some short pulses are given to the discharge filament in the interval between 2 and 5 sec. In this way, at each small step we observed that a large amount of electrons are brought to the surface. With continuous triggering, maximum electron signal was observed and a large amount of electrons landed softly above the helium surface (Figure 3). The maximum number of electrons on the surface is proportional to the potential difference between the top and the bottom plates, even though the electron density is about one order of magnitude less than the density for which the surface of helium becomes unstable[4]. This is the process through which we can ascertain the saturation of electron density over the helium surface. The technique is illustrated in Figure 3, where six pulses are given to the filament at intervals of a few seconds. After each pulse, a small amount of charge is deposited on the surface of helium. In this way, a maximum signal is observed that corresponds to the saturated electron density, $n_e = 8.76 \times 10^7$ cm^2 at electron temperature 1.68 K.

A typical trace of lock-in amplitude and phase signal for charged stable bulk helium surface versus time is shown in Figure 4. The charged surface was stable for several hours, as seen in the figure. After loading electrons up to saturation, as long as L^{4}He level and positive voltage on the bottom plate are maintained, the system was stable not only for several hours but also for a few days.

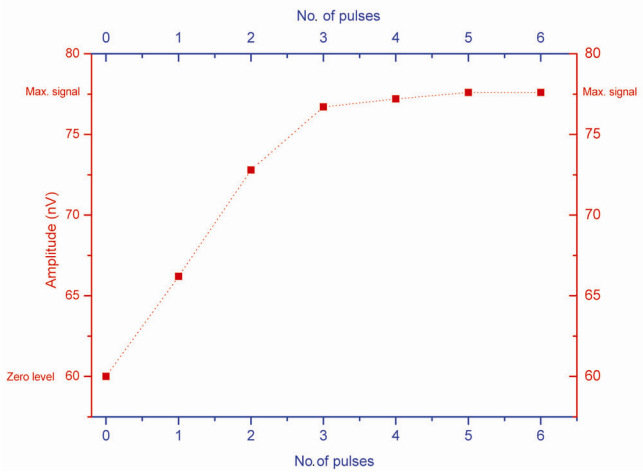

Figure 3. Charge observed after each pulse at liquid helium thickness, $d \sim 0.8$ mm, $V_{dc} = 12$ V, $V_g = -8$ V, cell temperature ~1.68 K and $n_e = 8.76 \times 10^7$ cm^{-2}.

However, changes in experimental conditions such as temperature rise, reduction of helium thickness caused by leak in the experimental cell, changing holding or guard voltages of electrodes during the measurement and/or strong mechanical vibration would cause loss of electrons.

In order to study the thermally activated escape, extracting voltage pulses were applied to the top electrode. Figure 5 illustrates this procedure by demonstrating the top-plate voltage pulse with the corresponding electrostatic barrier and the effect in the context of loss of electrons.

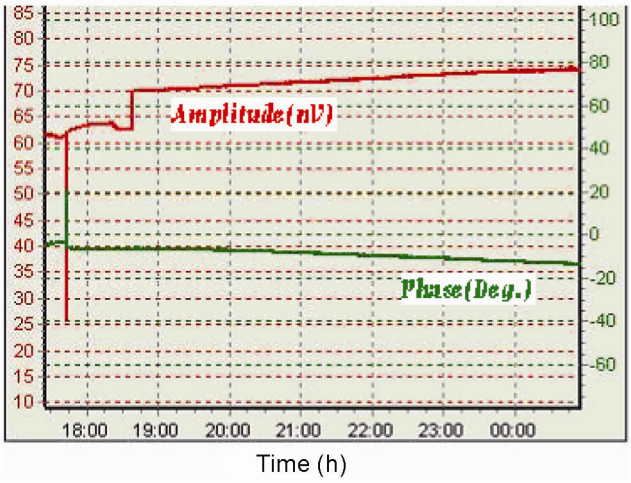

Figure 4. A typical lock-in trace (recorded) of signal (amplitude and phase) versus time. The surface was charged up to saturation. The stability of charged helium surface is illustrated for helium thickness, $d_{LHe} \sim 0.85$ mm and $V_{dc} = 3$ V, $V_G = -2$ V and $V_{top\text{-}plate}$ at ground potential.

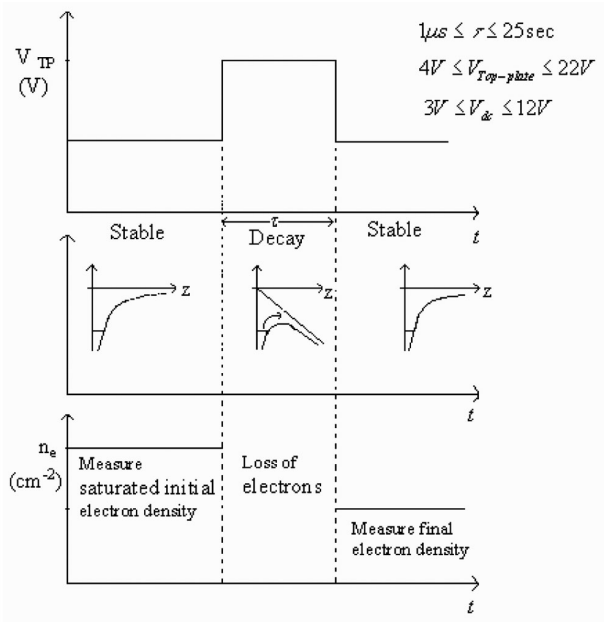

Figure 5. Positive voltage pulses imposed on the top plate, which are used to expel electrons from the surface of super fluid ^{4}He, corresponding electrostatic barrier of different extracting voltages, and saturated electron density as a function of time.

Under the influence of top-plate voltage pulses, extraction of electrons from the surface-bound state was accomplished. The surface was charged up to saturation. To observe the escape phenomenon of electrons, an extracting voltage was applied to the top plate using a pulse generator. The magnitude of the top-plate voltage must be higher than the holding voltage. Mathematically, $V = V_{TP} - V_{dc} > 0$. Then the pulse duration δt, was chosen sufficiently long so that most of the surface electrons that were deposited initially could be extracted. Such a process was repeated by reducing the timescale of the extracting pulse duration (i.e. pulse-width) until a single pulse did not cause loss of electrons anymore. The surface was charged up to saturation before each pulse. At each step, the lock-in signal was used to measure the signal of the charged surface and the remaining signal on the surface during or after the top-plate pulse. In this way, the amount of charge Δq leaving the helium surface in a pulse-duration Δt was measured. From the measured lock-in signal, loss of electron density was calculated using eq. (1). An example of measured data of amplitude of escaping electrons taken from the recorded lock-in traces as a function of pulse duration applied is shown in Figure 6. Here, each datapoint gives the final electron density of the remaining electrons after the top-plate pulse. All the analysed data presented were obtained using this process. From the present studies, we conclude that the escape of electrons strongly depends on the extracting voltage applied to the top plate and the pulse duration, δt. However, a fraction of electrons, $N = 4.4 \times 10^6$ electrons/cm^2 (i.e. approximately 6% of total charge density) remains at the surface even after imposing long pulse duration (Figure 6).

Therefore, probability of escape of electrons, $1/\tau$, after a 1 ms pulse duration is ≥94%. Such a behaviour is observed in all the measurements, although applying a pulse of higher extracting voltage, e.g. 22 V could reduce the remaining charge density down to ~2% of the original charge density. This might be due to the geometrical construction. With the electrode arrangement where equipotential lines above the bottom electrodes are zero, the extracting potential does not help to push out these remaining electrons. Hence, a fraction of electrons remains on the surface.

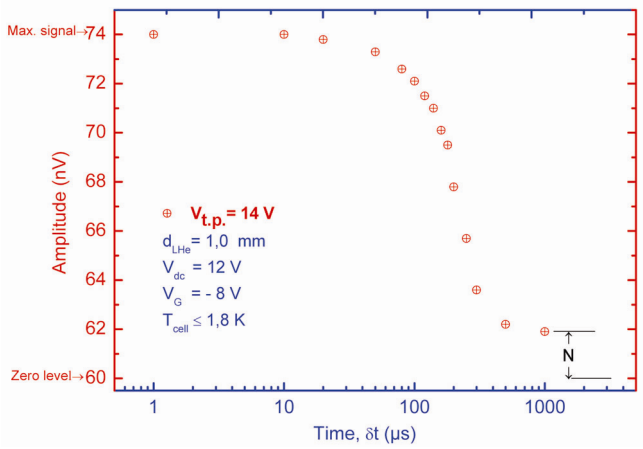

Figure 6. Amplitude of escaping electrons taken from the recorded lock-in trace as a function of imposed pulse duration through the top plate. $V_{dc} = 12$ V, $V_G = -8$ V, $d_{LHe} = 1$ mm, $n_e = 7 \times 10^7$ e/cm^2 and $V_{TP} = 14$ V.

A series of measurements were made to observe the effect of extracting voltage, V_{ext}, pulse duration, δt, L^{4}He thickness and temperature dependence on the escape phenomenon (R. K. Thakur and P. Leiderer, unpublished). A set of data was obtained by keeping other voltages and the liquid helium thickness constant, except extracting voltage that varied in the range $14 \text{ V} < V_{Ext} < 22$ V, where $V_{Ext} > V_{dc}$.

In every set of measurements, the surface electron density was calculated taking into account two datapoints. First, at remaining fraction of electrons after the longest pulse duration applied. Second, at saturation where a single shortest pulse did not cause any loss of electrons. From this, the transition time of 50% of escaping electrons from the surface was calculated (i.e. a datapoint was taken at 50% of escaped signal amplitude corresponding to V_{Ext} and imposed pulse duration through the top plate). Therefore, the transition time is the pulse duration that is longer than the electron transit time through the gas phase but shorter than the timescale which removes nearly all electrons from the liquid helium surface.

From the measurements we conclude that the escape of electrons depends on extracting voltage and pulse duration. Hence, transition time of 50% escaped electrons dropped with increase in the extracting voltage, V_{Ext}. In a simple model, such a behaviour can be qualitatively explained as follows: As soon as the extracting voltage is increased, the potential barrier is reduced which causes the escape of electrons. Similarly, the next set of measurements is done to study the influence of liquid helium thickness. So, all other parameters are constant; only the helium thickness is varied in the range of $0.4 < d_{L^4He} < 1.0$ mm. It is observed that the transition time of the electrons reduces under the influence of helium thickness (i.e. for increasing order of liquid helium thicknesses) due to the fact that the potential barrier decreases when the liquid helium level is far from the bottom electrodes, whereas it increases when the liquid level is placed close to the bottom electrodes. Since the liquid thickness determines the strength of the interaction between an electron and its image charge, it affects the potential binding of electrons to the surface. Therefore, measurements of the escape rates are density-dependent.

We have studied charging technique of liquid helium surface with three rectangular electrodes arrangement, and a stable electron density was observed for the set-up at temperature around 1 K. Besides, thermally activated escape of electrons from bulk liquid helium surface at the temperatures below 2 K was studied by applying external

voltage pulse to the top plate. More precisely, it is not possible to keep stable electron signals for long time above these rectangular bare electrodes. For this, the bulk liquid helium thickness should be higher than the gap between these electrodes, as illustrated in Figure 2. Only then the charged helium surface will be stable for longer duration.

We have demonstrated step-by-step charging process to achieve stable electron density for a long time duration. We have also found the minimum liquid helium level required to charge the surface and achieve stable electron density over ractangular electrodes arrangement. Such a charging process and stability parameters may give insights into the nature of thermal activation of 2D electrons at higher electron density over liquid helium surface and/or on a neon substrate coated with a thin helium film for potential applications in quantum computing using electrons on superfluid helium.

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Greenhouse gas emission and soil properties as influenced by wheat biomass burning in Vertisols of central India

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Biomass burning is a major contributor to the atmospheric carbon budget and increases the concentration of many trace gases apart from the adverse effects on soil properties. However, in many parts of India, crop residue burning is a recurrent and widespread practice for disposal of the residues after harvest of the previous crop to facilitate sowing of the succeeding crop. The residue burning on a larger scale also leads to severe atmospheric pollution. Against this backdrop, the present work was conducted to study the effect of wheat (*Triticum aestivum*) residue burning on soil properties and assess the potential greenhouse gas emission from burning of such residues on a regional scale. The study was taken up on farmers' field in Bhopal district, Madhya Pradesh, with two residue disposal methods, viz. residue burning and residue removal, for comparison with respect to their effect on soil properties and the greenhouse gas emission potential. No significant difference was observed between both methods in terms of soil organic carbon, inorganic carbon and available P content at 0–15 and 15–30 cm soil depths. Though residue burning showed favourable effect on available K content, there was reduction in the available N content in the 15–30 cm soil depth. Residue burning did not show significant effect on soil biological activity as estimated from fluorescence diacetate test. On the other hand, there was a significant adverse effect on soil structure and labile carbon content. Residue burning was estimated to result in the emission of 379 Gg C equivalent for India and 14 Gg C equivalent for MP.

Keywords: Biomass burning, greenhouse gas emission, soil properties, wheat.

CROP residue management and disposal after harvest of the previous crop is a common problem encountered by farmers of India. Less time gap between harvesting and sowing of subsequent crop, lack of requisite machinery for crop residue incorporation in the field and increased use of combine harvester to harvest wheat, leaves behind a large amount of unmanaged crop residue in the field[1]. In order to dispose of these residues quickly, farmers

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