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RESEARCH ARTICLE

# Quantum Carry Research of Q1D – SE on Helium at Charged Substrate

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**Abstract:** Known in nano-electronic a solid state quantum - size systems motivate they creating using the surface electrons over helium. The quantum carry of quasi-one-dimensional surface electrons (Q1D-SEs) over superfluid helium is considered here. Research performed according to an electron phase diagram in gas phase at conditions far from electron quantum melting. A substrate is dense row of the light-guide segments where the SEs channels are formed over helium in the fiber gaps. The electrostatic model of substrate profile demonstrates modulation of potential in the electric field leading to possibility of the fibers tops charge thereby improving the Q1D-SEs channels quality. The experiments carried out by a low - frequency electron transport method at the temperature from 1.5 K to 0.5 K and the concentrations of electrons were up to $10^9 \mathrm{cm}^{-2}$. The SE move transverse to channel satisfies conditions of quantization in sense both the temperature and the relaxation time of electron in a system. According to an experiment lower some temperature the SE conductivity is ladder-like. The differential of SE conductivity is peak-like corresponding qualitatively to an electron states density. The distance between peaks accords to the 1D energy spectrums in some approach. Possibility of apply the 1D-SEs quantized energy levels (vibration levels) as quantum bits of quantum computer is considered.

**Keywords:** quantum well, quantum wire, superfluid helium, surface electron, quantum bit

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## 1. Introduction

At structure size matter is comparative to electron de-Broglie wavelength the quantum effects are well expressed. Modern nano-technologies let create a clear quantum - size systems (QSSs) are use for both the fundamental researches and the applied purposes. The effects quantization of electron move in the quantum - size systems are observed at the electron energy spectrum resolution more temperature and at sufficient the relaxation time of electron in system. As was note the metal matter is not satisfied to QSSs conditions formation because both the high Fermi energy level (more 1 eV) and the small relaxation time of electron. The semiconductor matter can be candidate to QSS. The surface electrons (SEs) either on helium layers or on others cryogenic matters with smooth surface relate to the quantum - size systems too. Because both the low polarization of the substrate matter and the negative affinity it to electron the SEs move is quasi-free over substrate. The QSSs in nano-electronic are known as next: the quantum well; the quantum wire; the quantum dot; the heterostructure and others [1].

The specific properties SEs on helium surface was noticed in theoretical works [2] and [3] independently. Surface electron is localized in a shallow potential well and is distanced the surface. The Fermi energy of SEs, $\varepsilon_F = \pi \hbar^2 n_s /(2m)$, (here $\hbar$ is Plank constant; $n_s$ is concentration of 2D surface electrons; $m$ is the mass of free electron) is small enough relative to temperature so the electron system is nondegenerated. The SE move transverse to the substrate surface is quantized by the hydrogen-like spectrum as 7 K it the basic energy state and that is more the temperature in experiments. The SE mobility along the helium surface is high and it is limited only by both the interaction electrons with helium atoms in gas and the interaction with ripplons. The SEs Wigner crystallization at some conditions is proof of clean this system. The SEs system advantages are the broad variation both the electron density and the scatterers type in one experiment. The disadvantage of the SEs system on the massive liquid helium is limitation of the electron density near $2 \cdot 10^9$ cm$^{-2}$on value due an electro-hydrodynamic instability of charged surface leading to losses of the electrons either partly or full. The roughness of the solid substrate matter beneath helium layer can cause the thermo-activation carry of electrons. SEs serves as well the object of study and the conducting model of solid-state matter [4]. The surface electrons can be by basis the sensitive chips in nanoelectronic and by quantum bits (QB) of a quantum computer (QC) taking account here either the electron discrete energy levels or the electron spins [5,6].

The periodical modulation of the substrate properties leads the dimensionality of the surface electron system to one-dimensional (1D-SEs) or lower. For creating 1D-SE system the profiled substrate can be used. 1D-SE states on the bottom of the curvatured helium surface in the profiled substrate groove has been proposed and realized in works [7] and [8] correspondingly. The detailed theoretically description was performed in work [9]. In last work, in particular, the quantization of the electron collision frequency as function of the 1D-SE energy spectrums is considered at both the electron-ripplon interaction and the electron-He atom interaction. The narrow and clean electron stripes are need to the quantization of one-dimensional move. The influence of quantum effects on the electron carry is essentially and the simplest electron transport methods are enough for experimental research here.

The Q1D-SEs quantum effects researched in this work using the gaps between cylinder light-guides which filled by helium. According to an electron phase diagram the research was fulfilled in electron gas phase at the temperatures and at the surface electron concentration far from the quantum melting process.

The practical aims of many contemporary works are the theoretical and the experimental researches for creating a quantum bits on surface electrons for quantum computing [10-15]. Row of the internationals and nationals groups intensively give attention to this problem in last decade. The leader of the scientific group, Schuster David with collaborators (USA), and researcher Jin D study row questions: «Coupling a single electron on superfluid helium to a superconducting resonator; "Single electron on solid neon as a solid-state qubit platform" and related to them. Other group is Denis Konstantinov with collaborators (Japan). Their works dedicated row themes, for example, "Observation of the Rydberg's resonances in surface electrons over superfluid helium confined in a solid matter with 4-μm deep channel". Group performs much works concern to the novel devices projects and to the research of the fundamental basis for building the quantum bits over the helium or others cryogenic matters. So was created micro structured devise: superconducting coplanar-waveguide (CPW) resonator integrated with an electron trap for study "coupling of the SE spin states to the Rydberg's states". Separate theme is testing on SE move both the microwave radiation and the transition to Wigner crystallization. Others researches have deal with analogical questions using cryogenic matters or others as substrate and they give some example of qubits in practice too [16 – 19].

The possible building QBs on the vibration quantized levels of the one-dimensional surface electrons over superfluid helium which were preliminary considered in [20] is sense of present work. Works use the known basic consequences the Schrödinger and the Laplace equations at analyze 1D electron system. In current work the historical moment leading to the practical search 1D – SE energy levels is noted too. The bibliography is essentially supplemented here concern to study and designed QBs on surface electrons over cryogenic matters.

The original substrate for QBs in present work is combination micro-channels both the coaxial rings with $R$ and $r$ radius and the radial channels. The UHF technique with high quality cavity working on the $H_{011}$ oscillation mode for QB manipulations can be applied.

So, the current work has deal with the possibility creating QBs for QC using transverse oscillation of a one-dimensional electrons and that is considered in item 6 this work "Possibility apply a 1D-SEs quantization levels over superfluid helium as QBs of QC".

Original part of paper structure consists from next items: introduction; experimental setup; electrostatic consideration of a dielectric cylinder (light guide); experimental results; discussion; possibility apply a 1D-SEs quantization levels over superfluid helium as QBs of QC; conclusion.

## 2. Experimental Setup

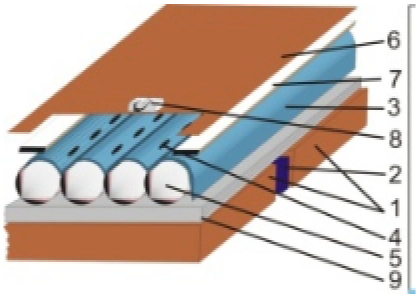
Building the clear Q1D system on the semiconductor basis motivates fulfill this system on the surface electrons basis. The work idea is creating relative narrow and stable Q1D-SE channels by added to the outer electric field the field of linear charges is placed directly on the profiled substrate tops. The coplanar field of charged stripes increases thereby the potential well and shifts surface electrons to the channel center apart from the groove borders. The Q1D-SE spectrum at that increases as value $\omega^2 \sim \pi^2 e^2 n_s / ma^2$(here $e$ is the charge of electron; $n_x$ is the linear charge density on the substrate tops and $a$ is interval between charges or the charge groups). The value $\hbar\omega$ can achieve the energy magnitude near 0.5 K.

Popular in the experimental research of SEs a low-frequency transport method is applied in this work. Conductance features of the Q1D electron system on the charged profiled substrate investigated by the Sommer-Tanner technique [21]. Method essence is analyzing conductivity of the charged system on substrate which coupled in the capacitive manner with the coplanar capacitor plates. The measurement some details concern to Q1D-SE channels can see in work [22]. The measurements werecarried out on the signal frequency 20 kHz at the value signal in range 2-150 mV rms. The temperature interval was from 1.5 K to 0.5 K and both the 4He and 3He refrigerators were used for temperature variation.

### 2.1. Cell

The design of cell in detailed is shown in Figure 1. The two neighboring plates 5x12 мм$^2$ in size (position 1) organized the measurement coplanar capacitor. Between measurements electrodes situated screening stripe 0.5 mm in section (position 2) function which is the crosstalk noises isolation. In parallel to measurement capacitor situated upper plate (position 6). The dielectric substrate with charges (position 5) is located inner to cell. Upper plate has negative potential for keeping charges on substrate with definition density. The guard ring (position 7) has negative potential and served for forming the electron spot with sharp borders.

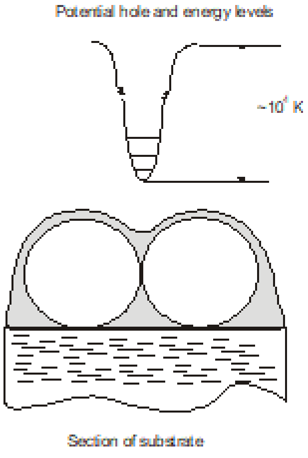
**Figure 1**
**Cell structure with profiled substrate for form the 1D SEs system: 1 - measurement electrodes; 2 - screening stripe; 3 - helium film; 4 - 1D system of surface electrons: 5 - substrate (row of light guides); 6 – electric clamping electrode; 7 - guard ring; 8 - electron source (glow tungsten thread); 9 – insulating plate**



The capacitive between parts of measurements electrode (position 1 on figure 1) without surface electrons on substrate is up to 80 fF and with SE on substrate that value is much more in magnitude. The measurement signal from generator directed to one measurement electrode and other one is connected with high sensitive two-phase lock –in- analyzer. The leading electric field has been directed along conducting channels. Measurements are performed on a current scheme because the impedance of SEs on the substrate much more input impedance the measurement system.

### 2.2. Substrate

**Figure 2**
**Substrate part section for forming electron quasi-one-dimensional channel over helium shown on figure 2: two the cylinder light guide segments withthe curved surface superfluid helium form channel for SEs (bottom picture); 1D potential well in clamping electric field with energy levels of 1D-SE (upper picture)**

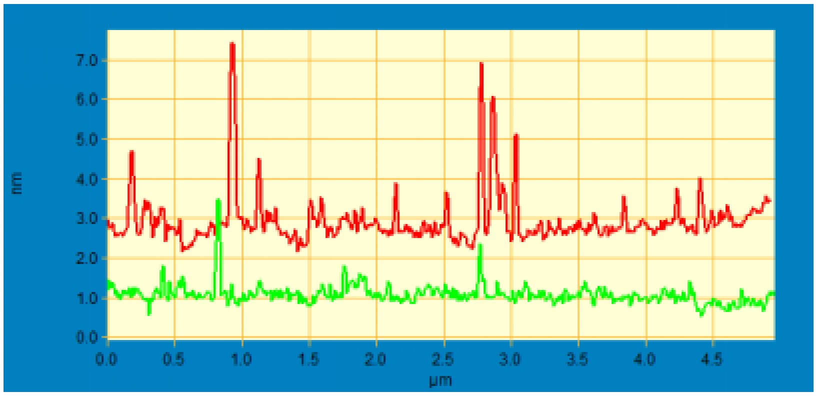


The profiled substrate represents a tightly laid row of light guides in quantity 35 segments by 100 µm in diameter situated on thin insulating plate (shown in Figure 1, positions 5 and 9). The superfluid helium flows on substrate into space between light guides creating the liquid curved grooves because both the capillary and the gravity forces. The liquid helium curvature radius in groove depends from distance substrate over massive helium. At presence of pressing electric field the grooves is filled by the SE lines over helium in the experiment process. On Figure 2 are shown schematically both the potential well for SE over curved helium surface between the cylindrical fibers (Figure 2, bottom picture) and the 1D energy spectrum in potential well (Figure 2, upper picture).

Preliminary, the some experiments performed on substrate where instead light guides use the nylon threads 90 µm in diameter which can charged spontaneously in outer field because quality.

The real fiber surface quality of light guide is different from ideal and its roughness has been defined by an atomic force microscopy (AFM) method (Figure 3).

**Figure 3**
**Atomic force microscopy (AFM) of the light guide surface (comment is beneath of picture)**



As can see on the AFM tracks, the roughness of the light guide surface is 0.7 nm rms in amplitude. The local inhomogeneity pikes are near 4 nm in amplitude with ~20 µm in interval. The effective electric potential variation along the conducting channel with SEs leads to the value which can express as next

$$\delta V \approx -\frac{\varepsilon_d - 1}{16(\varepsilon_d + 1)} \frac{e^2}{\pi \varepsilon_0 Z} \frac{\pi \xi}{A} (\frac{A}{Z})^{1/2} e^{-\frac{2\pi Z}{A}} \tag{1}$$

Here, $\varepsilon_d$ and $\varepsilon_0$ are the dielectric constant of both the substrate and the vacuum, accordingly; the value Z is the distance of surface electron to substrate; value $\xi$ is the inhomogeneities effective amplitude; and value A is the effective distance between inhomogeneities. The estimations give next: at equal the values A and $\xi$ and when the value Z is about $10^{-5}$-$10^{-6}$ cm in magnitude so, the effective potential variation, $\delta V$, is near magnitude $10^{-3}$ K the channel center. This value is increasing in magnitude near edge of border.

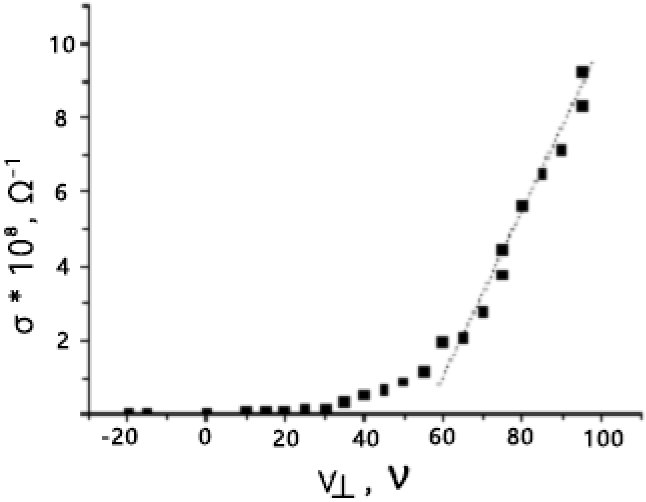
## 2.3. Procedure

Sequence the experimental steps is implemented as next. The nontermolized electrons from the glow tungsten thread (5 µm in diameter) were directed at some pressing electric field to tops of profiled substrate. Such are form a charged stripes with the fixed potential. (The electrostatic consideration possibility charging top of the dielectric cylindrical fiber is in item 3, beneath.) The slow moving thermolized electrons at the additional outer field are form conducting SEs channels on helium into the substrate grooves. The substrate electron density, $n$, either of the surface electrons or of the charged stripes has been determined by the values the specific cell capacitance with dielectric substrate, $C$, and the pressing potential, $V_\perp$, namely, $n = C \cdot V_\perp / e$ . At that has a place shift the conductivity dependence from $V_\perp$ to right on the potential axe is definition the charged stripes potential (Figure 4, for example).

The experiments carried out at different electron concentrations both the charged stripes and the surface electrons, beginning from zero magnitude electron density to value up to $10^9$ cm$^{-2}$ accordingly. The temperature dependences of SE conductivity are considered in item 4, "Experimental results".

**Figure 4**

**Example of shift to right the value $\sigma$ vs $V_\perp$ of SEs in the linear grooves of substrate at charged stripes. According dependence the potential of charged stripes is more 50 V. An extrapolation line by resection with potential axis is appointed this value magnitude. After that the SE conductivity behave, $\sigma$, is practically proportional to value $\Delta V_\perp$ (here $\Delta$ is difference in the potential values)**

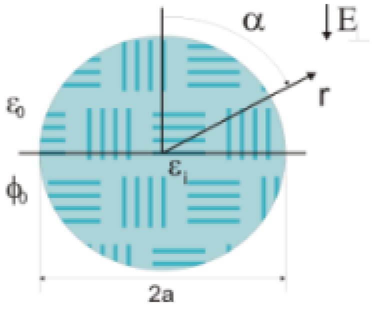


## 3. Electrostatic Consideration of a Dielectric Cylinder (Light Guide)

It is known the dielectric structured substrate in uniform electric field causes the electric potential variations in section. The analyze changing of the electric potential, $\varphi$, and the electric field, $E$, on the section of the surface dielectric cylinder top is considered here. The dielectric permittivity of light guide much more permittivity surrounding space, including liquid helium. Cross section of the cylindrical light guide in the coordinate system is shown on Figure 5.

**Figure 5**

**Cross section the cylindrical light guide in the cylindrical coordinate system: picture for electrostatic consideration. Here $r$ and $\alpha$ is radial and axial coordinates, accordingly; value $\varphi_0$ is the electric field potential outside the dielectric cylinder; values $\varepsilon_0$ and $\varepsilon_i$ are dielectric permittivity outside and inside cylinder accordingly**



Into cylindrical coordinate system ($r$ , $\alpha$) the Laplace's task at both conditions the perpendicular uniform electric field and the uncharged substrate is $\Delta\varphi = 0$ (here $\Delta$ is Laplace's operator and value $\varphi$ is the electric potential of dielectric cylinder). The variations of the electric potential along the cylinder axis in this coordinate system are absent, i.e. $d\varphi/dz = 0$. Take to account Fourier's replacement for $\varphi$ as $\varphi = M(r) \cdot N(\alpha)$ the Laplace's equation transform to next expression with a separating variables r and $\alpha$.

$$\frac{r}{M}\frac{d}{dr}(r\cdot\frac{dM}{dr})+\frac{1}{N}\frac{d^2N}{d\alpha^2}=0 \tag{2}$$

The suitable adjustment constants in the solution of each separate term in full expression are based on the equality both the electric potentials and the normal components of electric induction at cylinder border. According to solution terms of equation, the electric field either inside cylinder or near the cylinder border top or bottom, respectively, is

$$E_i = E_\perp \frac{2\varepsilon_i}{\varepsilon_i+\varepsilon_e} \tag{3}$$

Here value $\varepsilon$ is the dielectric permittivity of corresponding matter; symbols $e$ and $i$ are indices of the permittivity values outside and inside of cylinder, accordingly. The value of potential near cylinder border, $\varphi_e$ is

$$\varphi_e = E_\perp\left[\left(\frac{\varepsilon_i-\varepsilon_e}{\varepsilon_i-\varepsilon_e}\right)\cdot\frac{a^2}{r}-r\right]\cdot\cos\alpha+\varphi_0 \tag{4}$$

Summarizing out the electrostatic consideration of dielectric cylinder, should be note next:

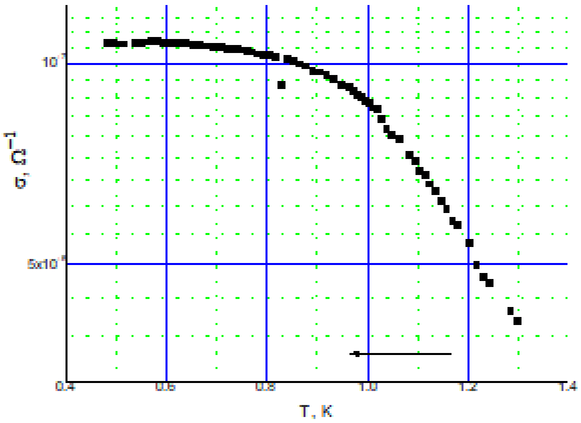
a) the intensity of electric field inside dielectric cylinder (and near top it surface) is twice more than outside cylinder at large dielectric constant of cylinder relative to surrounding matter (see expression (3));

b) the function [cos] is even then the electric potential is parabolic function on $\alpha$ near top cylinder border (see expression (4));

c) here takes place the possibility of the dielectric cylinders tops to linear charge because the parabolic potential well across cylinder.

## 4. Experimental Results

**Figure 6**
**Temperature dependence conductivity, $\sigma$, of quasi-one-dimensional surface electrons at condition absent the charge stripes potential on the profiled substrate is formed by light guides**

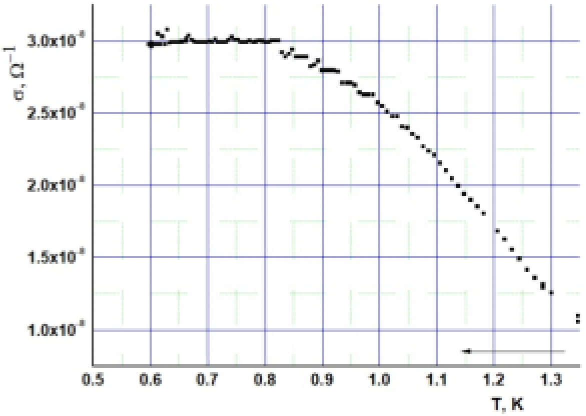


The calibration dependence a Q1D-SE conductivity, $\sigma$, from temperature, $T$, without the stripes charge on substrate demonstrates by Figure 6 aimed which is compare the result with others analogical dependences at the different values of potential both the SE and the charged profiled substrate. As can see on Figure 6 the dependence $\sigma$ from $T$ is smooth. The dependence is strong increasing more order at decreasing temperature from 1.3 K to 0.8 K (regime interaction surface electrons with He-atoms in gas phase). From 0.8 K to 0.5 K (preferential interaction surface electrons with ripplons on helium surface, helium gas go to freeze) this dependence is practically independent temperature. The mobility of SEs for the broad Q1D channel over liquid helium was considered early for these regimes. The mobility of SEs in the ripplon scattering region is $\mu_r = 8\alpha\hbar/emE{\perp}^2$ (here value α is the helium surface tension coefficient). The mobility of SEs in the helium gas scattering region is $\mu_g = 8e\ /\ (3\pi\hbar\sigma_p\ n_g\ \gamma)$ (here $\sigma_p$ is section scattering electron on the helium atom in gas; $\gamma^{-1}$ ~ 8nm is the Borh's radius for surface election over helium; $n_g$ is helium gas density).

The research results as the corresponding temperature dependences of conductivity at some the substrate charges potential and at some SE potential are shown beneath on Figure 7-12.

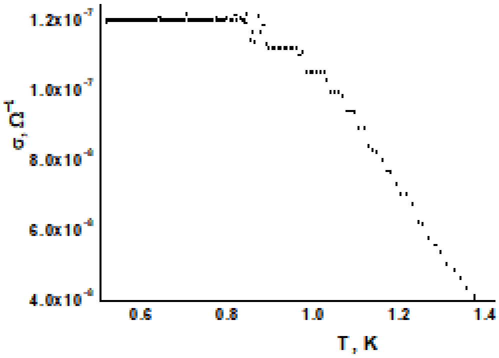
Before work with regular substrate (light guides on dielectric plate), as note upper (item 2.2, Substrate), the separate research has been performed with the nylon threads on glass plate which can be charge spontaneity because low quality of nylon thread. The some irregular conductivity in view small jumps observed at temperature lower than 1K (Figure 7).

**Figure 7**
**Temperature dependence conductivity of a Q1D-SE at spontaneity charged substrate with nylon threads on glass plate. This is first observation of irregularities *σ* vs *T* dependence. In temperature range between 1.0 K – 0.83 K takes a place irregularities the type of small jumps**



On Figure 7 presented experimental investigation irregularities as conductivity from temperature performed early with using as profiled substrate the nylon threads 90 µm in diameter on glass plate. It is shown the temperature dependence conductivity of Q1D-SE at spontaneity charged substrate has a place the irregularities in temperature range between 1.0 K – 0.83 K as small jumps.

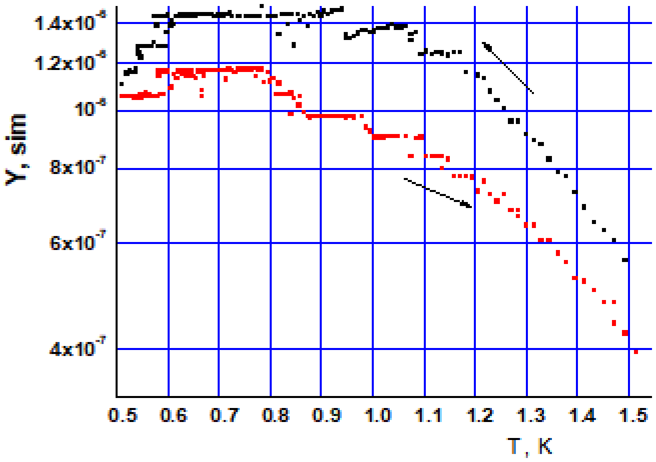
**Figure 8**
**Temperature dependence of Q1D-SE conductivity, *σ*, in channels at small stripes charge (beginning research with stripes charge on the light-guides tops)**



On Figure 8 at temperature range from 1.4 K to 0.8 K we can see the exponential dependence of Q1D-SE conductivity which due scattering electrons with He atoms in gas (the He gas region); ripplon scattering regime has a place at $T< 0.8$ K. Bat here take a place a ladder-like view of conductivity at temperature interval lower 1.1 K. This feature due by quantization Q1D-SE curry and steps is the more expressed with lowering temperature. Last can explain increasing an immobile SE with decreasing $T$ near some roughness of channel border because termo-activation effect. The part of immobile SE increases 1D potential well and shifts mobile SE to the channel center.

**Figure 9**

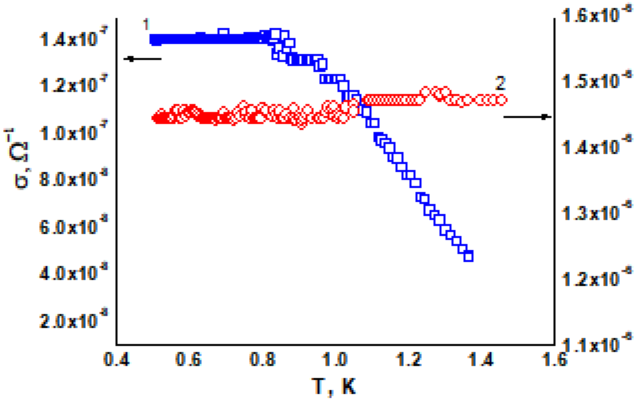
**$\sigma$ vs $T$ dependence of Q1D- SEs is measured at the substrate charge potential, $V$, approximately 5 V: upper curve is obtained at cooling cell from 1.5 K to 0.5 K at start of this research and under curve takes a place at increasing temperature of cell from 0.5 K to 1.52 K in same experimental process**



In begin the substrate with not enough high quality of the glass surface had been used for obtaining the temperature dependences of conductivity. The upper arrow of figure 9 indicates the lowering temperature at start the experiment and under arrow and lower curve related to increasing temperature (return move) of this experiment. At temperature lower 1.2 K the conductivity ladder-like steps have a place on both curves but more clean steps demonstrates the bottom curve. It is supposed has place tend to the redistribution order of electrons along each stripe during some time relative previous dependence.

**Figure 10**

**Dependence conductivity, $\sigma$, of Q1D-SEs from $T$ at high electron concentrations both the SEs and the stripes charge: the upper conductivity dependence, curve 1, was measured at electron densities near $5.4 \cdot 10^8$ cm$^{-2}$ (here is left axe for conductivity) and the under conductivity dependence, curve 2, was measured at the electron densities ~$10^9$ cm$^{-2}$ (here is right axe of the conductivity) correspondently. The cycling on $T$ practically not changes this dependence**



At high electron densities both the SEs and the stripes charge of temperature dependences Q1D-SE conductivity are shown on Figure 10. Here curve 1 is dependence conductivity at electron densities near $5.4 \cdot 10^8$ cm$^{-2}$ at cooling of the experimental cell. The curve 2 is conductivity dependence at the electron densities ~$10^9$ cm$^{-2}$ at the cell heating. It can to see on Figure 10 the maximum of a quantization step of conductivity is approximately 0.5 K (curve 2) and that corresponds to 3 cm range of irradiation. So the 3 cm technique can be uses for spectroscopic study and manipulations in this case.

**Figure 11**
**The temperature dependence of Q1D-SEs conductivity, *σ*, after row of the cycling passages on *T*. Here the potentials15 V have a place for both the charged stripes and the SEs**

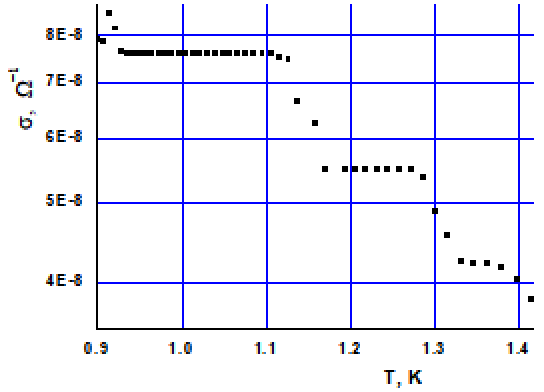


**Figure 12**
**Differential temperature dependence of Q1D-SEs conductivity is given on Figure 11**

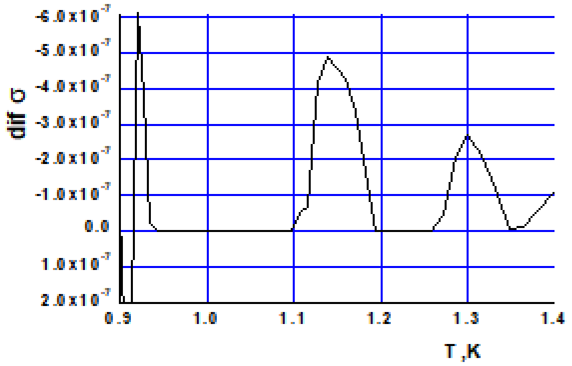


Figure 11 and 12 demonstrate the temperature dependence of Q1D-SEs conductivity and the differential of that value in temperature interval 0.9 – 1.4 K for high quality substrate (after cleaning). The results are applied after row the temperature cycle passages on temperature. The SE potential and the stripes charge potential have values 15 V. It can see dependence *σ* vs *T* on Figure 11 is well expressed as ladder-like with steps increasing with decreasing temperature. The differential that value has a pick-lake character (Figure 12) which qualitatively coincides with the electron states density.

Summing up the experimental results need notice next. The substrate charge is used for improving the SEs channels quality by increasing 1D potential well. The SE quantization move is manifested itself as the conductivity ladder-like dependence from temperature. The steps duration depends on the electron densities both the Q1D-SEs potential and the substrate electron charges. Steps duration are varied in researches from zero (without the substrate charge, Figure 6) to near 0.5 K in value (Figure 10, curve 2). The energy intervals of Q1D-SE spectrum accord to the steps duration and the differential of the conductivity temperature dependence (Figure 12) is qualitatively coinciding with the electron state density.

## 5. Discussion

As appointed above the effects of quantization electron move in QSSs are observed at the energy spectrum resolution of electron, $\Delta\varepsilon$, more temperature, $T$, and at the relaxation time of electron in system, $\tau$ , is sufficient, i.e. $\varepsilon_{n+1} - \varepsilon_n > k_b \cdot T$ and $\varepsilon_{n+1} - \varepsilon_n > \hbar / \tau$ . According to solution of stationary Schrodinger ' s equation for 1D surface electron at the parabolic potential, $U(y) = m\omega_0^2 y^2 / 2$ , wave function of basic electron state is

$$\psi(y) = \pi^{-1/4} y_0^{-1/2} \exp\left(-\frac{y^2}{2y_0^2}\right) \tag{5}$$

Value $y_0^2 = h / (2\pi m\omega_0)$ is the SE localization length square cross channel.

The harmonic spectrum size of a 1D electron system corresponding to frequency, $\omega_0$, in potential well (see Figure 2) is

$$\omega_0^2 = e \cdot E_\perp / (m \cdot R) \tag{6}$$

The value $R = \sigma / (\rho \cdot g \cdot h)$ is the curvature radius of liquid surface in groove (here $\sigma$ is the surface tension of superfluid helium and $\rho$ is the helium density; value g is gravity constant) which in experiments take a place 35 μm in size. The energy spectrum of one-dimensional electron at parabolic potential is

$$\varepsilon = (n + 1/2) \cdot \hbar \cdot \omega_0 + \hbar^2 \cdot k_x^2 / 2m \tag{7}$$

Value $k_x$ is the wave vector of an electron along conducting channel.

The depth of 1D potential well over helium in groove of profiled substrate can estimate as $\varphi \sim e \cdot E \cdot \delta$ (here value $\delta$ is a deflection the liquid surface from horizon in groove).

Notice, estimates according [8] are give next magnetudes: $\varphi \sim 10^4$ K; $\hbar\omega_0 \sim 0.1$ K and $y_0 \sim 30$ nm at clamping electric field $4.5 \cdot 10^4$ V/m in magnitude. As considered upper the linear charges of a stripes tops shift Q1D-SE inter energy lines of spectrum and magnitude that value can achieve more 0.5 K.

The inhomogenates have a place on profiled substrate in spite of cleaning one (Figure 3). That leads to the thermo activation carry of electrons. According Arrhenius law the conductivity of channels expressed as $\sigma = \sigma_0 \cdot \exp \Delta / T$ (here $\Delta$ is energy of thermo activation; $\sigma_0$ is the conductivity of clean channels). The effective magnitude of value $\Delta$ in most experiments was near 1 K.

So number of immobile electrons near the boundary is increasing with decreasing $T$ and they can add to the linear electron charge on structured substrate and that increases the potential well for SE.

## 6. Possibility Apply a 1D-SEs Quantization Levels over Superfluid Helium as QBs of QC

Researchers Platzman and Dykman considered opportunity creating QC using two-dimensional surface electrons (2DSEs) over superfluid helium covering periodical set of governing electrodes [5]. The basic energy level and the first excited energy level of SE as quantum bit (QB) were proposed use. Both the SE Rydberg's levels and they Stark's shift by electric field accord to outer microwave energy are considered. The Wigner's crystallization of SEs leads to the entanglement of electron states. The quantum ionization of the excited electrons into the free space through adjustable potential barrier for read-out the electron states are proposed.

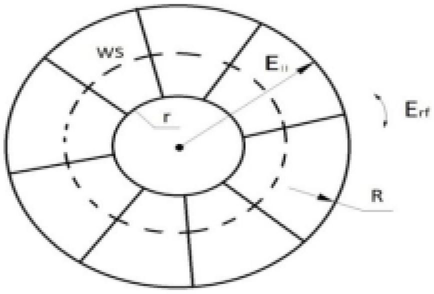
In our original work is considered possibility building QBs use the transverse vibration energy levels of one-dimensional electrons over liquid helium (energy levels schematic shown simile on Figure 2, upper part). The upper performed investigates of quantized move in Q1D-SE is basis for consideration that proposition. The substrate is combination of the micro-channels by value $\delta$ in cross section arranged as coaxial rings with $R$ and $r$ radius which are connected each other by same radial channels (Figure 13). The SE can move along radial channel between rings by the radial electric field. The substrate can be situated in a cylinder superconductivity UHF cavity with high quality factor of the $H_{011}$ mode.

Over nodes of the large radius ring in pressing electric field are formed the 1D-SEs vibration energy levels $\hbar\omega_0$ with the wave functions basic state like (5). The frequency of equidistant spectrum, $\omega_0$ , is shown in (7). The quantized vibration states of surface electron are considered as a qubit basis. The Q1D-SE superposition state of QB is defined by the Rabbi's frequency pulse or by shift the UHF pulse is caused clamping electric field. The Rabbi Frequency is

$$\Omega = \frac{eE_{rf} <0|y|1>}{\hbar} \tag{8}$$

$E_{rf}$ is intensity of Rabbi electric field, cause the transition of SE between the vibration energy levels <0> and <1>.

**Figure 13**
**Combination of 1D micro-channels for QBs of QC: the coaxial micro-channel rings with large, *R*, and small, *r*, radiuses are connected each other by same radial micro-channels**



The entanglement of the electron states has a place at the Wigner's crystallization of SEs (signed as dashed line on Figure 13), which manifested at corresponding ratio the potential energy of the Coulomb interaction between electrons to the kinetic energy, in particular, thermodynamic one, namely,

$$e^2 (\pi \cdot n_s)^{1/2} / (4 \cdot \pi \cdot \varepsilon \cdot \varepsilon_0 \cdot k_B \cdot Tc) = \Gamma. \tag{9}$$

Were $\Gamma^{-1} = 1/\ 137.035$ is constant of the thin structure, $k = 1.38 \cdot 10^{-23}$ J/K is the Boltzmann's constant, $\varepsilon$ and $\varepsilon_0$ are dielectric permittivity the substrate and the vacuum, accordingly.

As appointed in current researcher (Figure 10, curve 2) the value 0.5 K of the energy quantization level can be achieve in Q1D-SE vibration specters and 3cm technique can be considered for QB manipulation.

Read out of the Q1D-SE state after reverse moving can be detected either by the micro-capacity or by the SET (single electron transistor). Estimates can be next. The radiuses magnitudes are $R \sim 1$ mm and $r \sim 0.1$ mm accordingly; $\delta \sim 1\text{-}2$ μm; the UHF-cavity $H_{011}$ resonance is 9.4 GHz (the 3 cm technique), were value $\Delta\varepsilon = \hbar \cdot \omega_0$ is ~ 0.5 K. Near a small diameter ring the electron crystal goes to melt at temperature near 20 mK. The surface electrons quantity can achieve value $5 \cdot 10^2$ over nodes and that can be the QC scale. It must be note the quality of cavity with superconducting coating (Sn matter, for example) can achieve $10^{10}$ and more in magnitude.

## 7. Conclusion

Summarizing must note next. Studded of the quantum carry features of quasi-one-dimensional surface electrons over the superfluid helium at charged substrate the energy levels which can applied to building a quantum bits. According to idea the charge of a profiled qualitative substrate can to improve essentially the SEs conducting channels by increasing 1D potential well. The researches were performed in the electron gas phase.

The substrate profile in the electrostatic model according to Laplace's task at both conditions the perpendicular uniform electric field and the uncharged substrate demonstrates modulation of potential giving possibility for the substrate tops to charge. The experimental profiled substrate represents tightly laid on insulating plate a row of the cylindrical light guide segments by 100 μm in diameter. The superfluid helium flows on substrate into space between light guides creating the liquid curved grooves caused both the capillary and the gravity forces. In the experiment process the grooves filled by the SE lines over helium.

The low-frequency electron transport method which is popular at study the low dimensional surface electrons was applied here. The ladder-similar dependence $\sigma$ vs $T$ in experiment was displayed on profiled substrate using the light guides. The step picture depends on the electron density both the Q1D-SEs and the substrate charge. The steps can vary from zero (without the substrate charge, Figure 6) to near 0.5 K in value (Figure 10). The energy intervals of Q1D-SE spectrum accord to the ladder's steps duration as supposed. The differential of dependence the surface electron conductivity from temperature is pikes-similar and it qualitative corresponds to the electrons state density. The steps of conductivity don't depend on the measurement signal parameters, bat they dependence from the substrate surface quality. The experimental investigation the irregularities of conductivity from temperature were performed early with using profiled substrate on the nylon threads 90 μm in diameter. It was shown (Figure 7) the temperature dependence of Q1D-SEs conductivity at spontaneity charged substrate not high quality has irregularities. In temperature range between 1.0 K – 0.83 K is observed a small jumps.

More pronounce steps on the conductivity dependence at decreasing temperature can be explained by both the electrons redistribution to the lower energy levels Q1D system and the increasing of number of immobile electrons near the channels boundary according to Arrhenius ' s law. The experimental investigation coincides with theoretical consideration at some approximation.

It is possible apply the 1D-SEs quantization levels for QBs building and the 3cm technique can used here for QB manipulations. QBs state can govern both the electric field pulses and the UHF pulses. Designed set of 1D micro-channels is arranged as coaxial rings with $R$ (outer) and $r$ (inner) radius which connected each other analogical radial channels (Figure 13). The SEs can move between rings by the radial directed electric field and the SEs states entanglement is possible at electron Wigner crystallization in space between rings.

In recent works [23, 24] were shown that an electrons floating in a vacuum above the surface of liquid helium or solid neon emerge as promising candidates for qubits. Charge qubit consisting of a single electron bound to solid neon surface exhibits an exceptionally long coherence time. By evaluating the surface charges induced by the electron was demonstrated its strong perpendicular binding to the neon surface. The Schrodinger equation for the electron's lateral motion on the curved 2D surface is then solved at extensive topographical variations. The results reveal that surface bumps can naturally bind an electron, forming unique ring-shaped quantum states. It was shown the electrons excitation energy can be smoothly tuned using a magnetic field to facilitate qubit operation. Were considered too both the theoretical proposals and recent experiments, primarily focusing on the use of the spin state as the qubit, wherein the spin and charge states are hybridized. Throughout these proposals and experiments, the charge state is coupled to an LC resonator, which facilitates both the control and readout mechanisms for the spin state via an artificially introduced spin-charge coupling.

It must note, the others cryogenic solid matters at the convenient quantum characteristics with or without helium film can used as substrates instead helium and neon: for example, $H_2$, $D_2$, Kr and others. For the neon substrate the quantum values are the binding energy of electron with the substrate is $E_{bin}$ = 17.5 meV and the Bohr radius, $\gamma^{-1}$, is 19 Å, respectively. For the solid hydrogen substrate the binding energy of the electron with the substrate is $E_{bin}$ = 16.7 meV and the Bohr radius is 17 Å, respectively, and for the solid deuterium $E_{bin}$ = 22 meV and $\gamma^{1}$ is ~ 15 Å, respectively.

Recently a silicon spin many qubits processor was proposed in work [25]. Compact 3D microwave dielectric resonators were considered as a way to deliver the magnetic fields for spin qubit control across an entire quantum chip using only a single microwave source. Here take a place "coherent Rabi oscillations of the single electron spin qubits in a planar SiMOS quantum dot device at using a global magnetic field generated off-chip".

## Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

## Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

## Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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## Author Contribution Statement

**Viktor A. Nikolaenko**: Conceptualization, Methodology, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization. **Sviatoslav S. Sokolov**: Software, Validation, Formal analysis, Data curation, Writing - review & editing, Visualization, Supervision, Project administration.

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