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Light Emission from Silicon Structures with Dielectric Insulation

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The paper presents the results of an experimental study of the current dependence of samples of silicon structures with dielectric insulation (SSDI) on voltage, and describes the features of the flow of currents of extremely high density in these structures. A study of the processes of self-organization of electron-hole plasma in SSDI manufactured using SDI technology and an analysis of the obtained results have been performed. The temperature T_i of intrinsic conductivity, which was 860 K, was experimentally determined at a current density of less than $2 \cdot 10^4$ A/cm^2, which exceeds the temperature in the structures made by "silicon on insulator" (SOI) technology by more than 200 K. It is shown that the current causes an intense Joule heating of these structures, an emergence of their own conductivity and the electron-hole plasma formation. A plasma stratification is accompanied by a glow in the form of symmetrically located red spots. The appearance of each new spot is accompanied by the formation of an S-shaped area on the volt-ampere characteristic, which is a typical manifestation of the current cord formation. The current cord occurs if the characteristics of the current dependence on the voltage (*I-U*) of SSDI structures deviate from the Ohm's law, having an S-shape. The appearance of cords is inherent to materials, in particular semiconductors, with the electrical conductivity increasing rapidly with temperature growth, due to the increase in charge carrier concentration. The obtained results are compared to authors' earlier results of studies of light emission from the structures produced by SOI technology. It was found that the effects in the SOI structures occur at lower current density values than in the SSDI structures.

Keywords: Silicon structure with dielectric insulation, Extremely high-density currents, Joule heating, Light emission.

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1. INTRODUCTION

Extremely high-density currents in semiconductor structures cause their intensive Joule heating. The effects associated with Joule heating can significantly affect the operation of devices based on such structures. In particular, in structures created using the well-known "silicon-on-insulator" (SOI) technology [1], the sample is separated by a thin layer of silicon oxide (SiO_2) from a massive silicon substrate, which is an effective heat sink. In fact, this structure is a field effect transistor (FET). Under these conditions, extremely high-density currents can flow through the working layer of silicon.

Powerful oscillations of the current while powering SOI structure in the voltage generator mode [2] was observed. When applying voltage pulses of rectangular shape, the initial section of the *I-U* curve of SOI structure was typical for FET [3]. At first, the current increased linearly, then its saturation occurred. At further increase in the amplitude of the voltage pulses, a single peak of current arises on the current pulse. Moreover, the amplitude value of the current was order of magnitude higher than it was at the base of the peak. The number of current peaks increased with increasing amplitude of rectangular voltage pulses.

While powering them in the current generator mode, we observed light emission in the form of separate spots located symmetrically across the sample near the drain of the SOI FET [4]. As in the previous case, the initial section of the *I-U* curve was characteristic of the FET. In this area, there was a yellowish-white glow in the form of a strip near the drain parallel to it. The appearance of the first red spot was accompanied by an S-shaped section on the *I-U* curve. As the current increased, each subsequent spot was also accompanied by an S-shaped section. In addition, in diffusion resistors prepared using "silicon with dielectric insulation" (SDI)-based technology a nonlinearity of *I-U* curves was observed, meaning a change in resistor resistance [5], which is unacceptable for the stable operation of devices. Such unusual phenomena can significantly affect the operation of SOI- and SDI-based devices. All these phenomena were observed at current densities $j \sim 10^5$ A/cm^2 and high electric field strengths $E \sim 10^5$ V/cm. In this case, the specific power dissipation exceeded $P \sim 3$ GW/cm^3 without destroying the sample. Such extreme conditions cannot be realized in bulk semiconductors, but in thin films that form the basis of semiconductor devices, their realization is quite probable.

Such currents cause the structure Joule heating up to the temperature of intrinsic conductivity and occurrence of electron-hole plasma in semiconductor [2, 3]. Because of the fact that each regular red spot occurrence in the SOI structures is accompanied by an S-shaped section in the *I-U* curve, the stratification and self-organization of electron-hole plasma took place. The phenomenon of electron-hole plasma self-organization in silicon structures has been poorly studied but has a significant effect on the operation of semiconductor devices.

Therefore, the aim of the present work was to investigate the electron-hole plasma self-organization in structures prepared using SDI-based technology – silicon structures with dielectric insulation (SSDI).

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2. EXPERIMENTAL RESULTS AND THEIR DISCUSSION

2.1 Experimental Samples

The experimental samples of silicon $n^+ - n - n^+$ structures were prepared using SDI-based technology and were located in the so-called "pockets". They are shown schematically in Fig. 1.

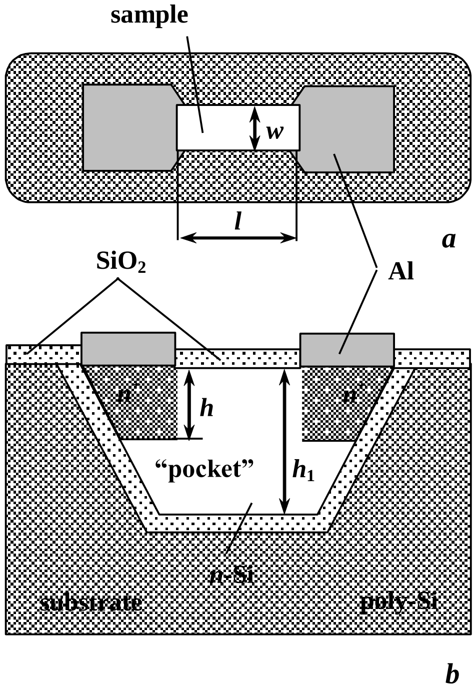

Fig. 1 – Experimental SSDI sample: a – top view of the SSDI sample, b – its longitudinal section

The substrate is of 300 μm polysilicon. The "pockets" had different depths $h_1 = 2.8\ldots10.5$ μm. They were isolated from the substrate with a 2 μm thick layer of SiO_2.

The experimental samples were prepared from single crystalline n-Si with a thickness of 0.4 μm and with the initial concentration of charge carriers $n \sim 10^{17}$ cm^{-3}. For different samples, the length of the channel was $l = 9\ldots70$ μm, width $\omega = 10\ldots100$ μm. n^+-regions were obtained by ionic doping of silicon with phosphorus with subsequent thermal immersion to depth $h = 5$ μm. Electrical contacts to n^+-regions were prepared from aluminum.

From above, the structure was coated with a 1 μm thick SiO_2 layer, allowing observation of the surface in an optical microscope.

In the work presented, only those samples were used, for which the depth of the "pocket" coincided with the depth of the doping of the contacts, i.e. $h_1 \approx h$. This was necessary to ensure the uniform flow of current in the sample channel required to determine the temperature of its heating.

2.2 Experimental Technique

Block-diagram of the experiment is shown in Fig. 2. The SSDI experimental sample was powered by a DC source. The *I-U* curves were recorded.

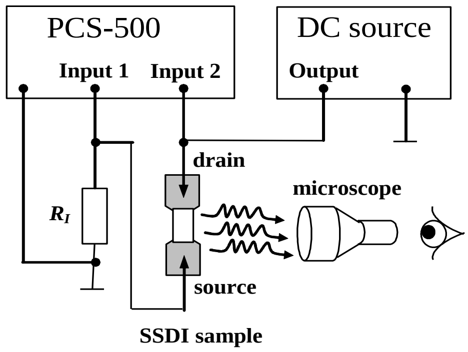

Fig. 2 – Block-diagram of the experiment

The current value I was determined by the voltage drop U_I proportional to its value on the resistor R_I. Resistance of R_I was selected in such a way that even when changing the resistance of the SSDI (R_{SSDI}) under the conditions of the experiment, a ratio $R_I \ll R_{SSDI}$ would always be fulfilled.

Voltage drop U was taken directly from the DC source output, since the voltage redistribution between the sample and the resistor R_I can be neglected.

The electrical signal was taken from the structure by tungsten probes.

Both U_I and U voltages were applied to the inputs of the computer oscilloscope PCS-500.

Light emission from the structure was recorded by an optical microscope at × 100 magnification. Video camera was mounted in one of the microscope eyepieces, the image from camera was captured. The operating range of the camera captures the visible region of the spectrum and the near infrared. Therefore, the images captured by the camera could differ from those seen by the eye with strong heating of the structure.

2.3 Experimental Results

A typical *I-U* curve is shown in Fig. 3 for the SSDI sample with the "pocket" depth $h_1 \approx h = 5$ μm. The size structure was chosen with the length of the channel $l = 10$ μm and width $\omega = 10$ μm.

There are those planar dimensions that had SOI structures, where the stratification of the electron-hole plasma and light emission were observed for the first time [4].

For structures with other sizes, the results differed quantitatively but not qualitatively.

The numbered points in Fig. 3 correspond to the photographs in Fig. 4. The initial section of the *I-U* curve is linear. There is no light emission from the structure at this section (Fig. 4, photo 1).

As the voltage drop increases further, current saturation is observed. The saturation of the current was accompanied by the appearance of a region of yellowish-white glow in the SSDI sample along the drain. Initially, the glow line is broken (Fig. 4, photo 2). As the current increased, the size of the glowing area also increased, and the yellowish-white glow became a solid line (Fig. 4, photo 3).

With further increase in the voltage drop on SSDI, an S-shaped section was observed in the *I-U* curve. The yellowish-white glow faded, and then one red spot appeared at the same place (Fig. 4, photo 4). This spot was located on the longitudinal axis of the sample, but moved closer to the drain area of the structure.

Further increase in the current through the sample was accompanied by a decrease in the voltage drop on SSDI. The brightness and intensity of the spot glow decreased (Fig. 4, photo 5). Next, the following S-shaped section was observed. On it, the intensity of the glow of one spot diminished, and then it split into two spots (Fig. 4, photo 6). The diameter of the both these spots was less than the diameter of the first one by about half. They were located symmetrically relative to the longitudinal axis of the sample and also closer to the drain.

The next S-shaped section in the *I-U* curve was accompanied by a similar decrease in the intensity of the spot glow, and then three symmetrically located spots were formed along the junction of two spots: one on the longitudinal axis of the specimen, two on either side of it (Fig. 4, photo 7). The diameter of these spots is even smaller compared to the size of the two spots.

The transition from the glow of three spots to four is illustrated by photos 8 and 9 in Fig. 4. In contrast to the formation of new spots on the previous S-shaped sections, further increase in current caused the appearance of glow also near the source of the structure (Fig. 4, photo 10).

Light emission from those four spots was perfectly observed in the optical microscope. Unfortunately, the camera failed to capture them. In photo 10 in Fig. 4, the spots merge as the camera's sensitivity area captures the near-infrared portion of the spectrum. As the structure intensifies heating, the contribution of infrared radiation becomes more significant than the contribution of the optical spectrum, as the camera registered.

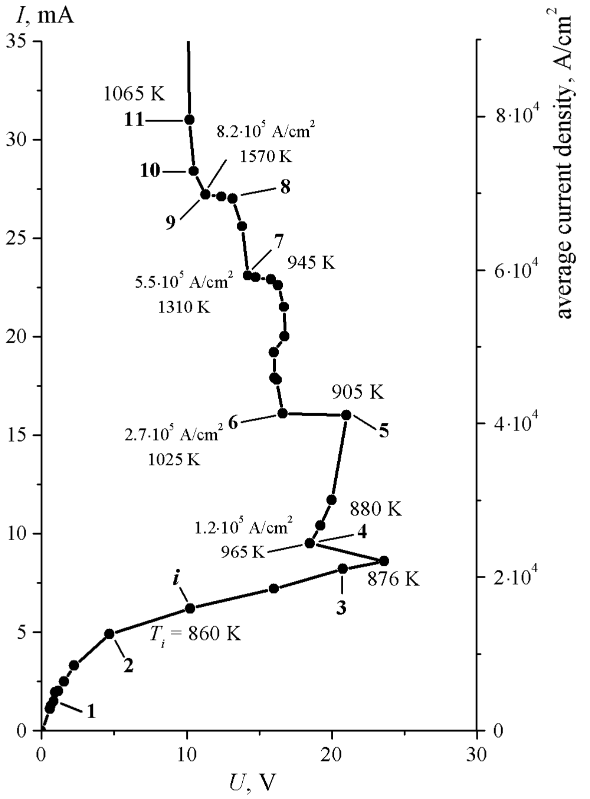

Fig. 3 – *I-U* curve for the structure with the "pocket" depth $h_1 \approx h = 5$ μm, channel length $l = 10$ μm and width $\omega = 10$ μm

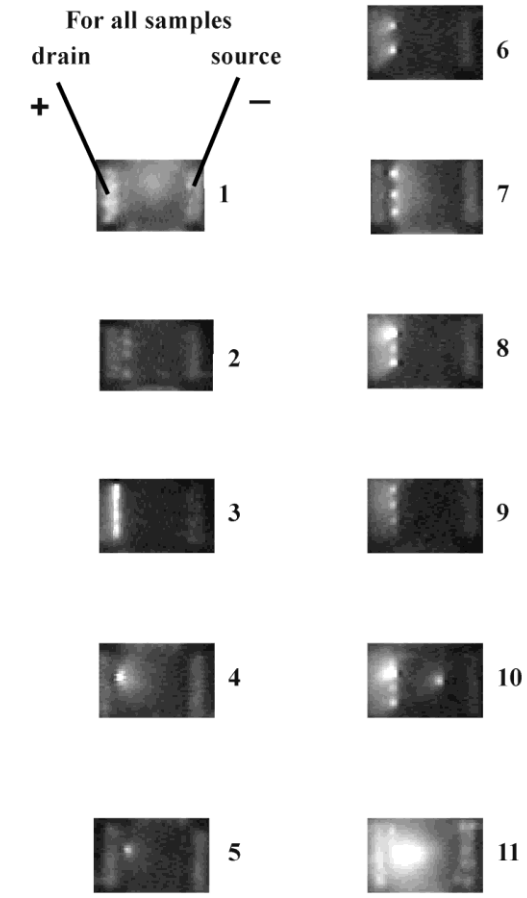

Fig. 4 – Photos of the light emission from the SSDI. The photo numbers correspond to the numbered dots in Fig. 3

Before the first red spot occurred, the *I-U* dependence was reversible. With all subsequent measurements the curve was repeated without any modification, irrespective of the direction of current variation. With the appearance of red spots, the *I-U* dependence becomes irreproducible, but irreversible changes occur within the measurement error and are not shown in Fig. 3.

With a further increase in the current, a breakdown of the sample occurred. Photo 11 in Fig. 4 shows the appearance of a powerful orange glow, which subsequently linked the source and drain. Immediately afterwards, the silicon of the film was thrown out from the sample, resulting in its destruction.

It should be noted that a significant difference between the *I-U* curves of the SSDI and SOI structures is that as the current in the SSDI increases, there is a general tendency to decrease the voltage drop, while the SOI structure *I-U* curve has an increase.

2.4 Discussion

Linearity of the initial section of the *I-U* curve followed by its saturation is characteristic of the FET [3]. SSDI does not contain a gate, as well as SOI [2]. The role of the gate is played by the substrate or the ohmic contact to the substrate. Such structures have been classified as pseudo-FET (or ψ-FET) [6].

According to Fig. 3 and similar data for other samples, the specific power dissipated in SSDI was estimated. The average specific power density reaches 0.9-

3 GW/cm^3 for different samples. This coincides in order of magnitude with the data for SOI (1-5 GW/cm^3) [2]. According to the experimental data of the *I-U* curve (Fig. 3) current densities were calculated. Since the current flow is nonuniform at the stratification of electron-hole plasma, the average density values are shown in Fig. 3. In fact, local current densities can far exceed the specified values.

When comparing the results obtained for SSDI samples with those obtained on SOI structures [4], it should be noted that the observed effects occur at lower current density values. For SOI structures, the average current density reaches values of 10^6 A/cm^2, while it does not exceed the value of 10^5 A/cm^2 for SSDI. In particular, in the sample for which the *I-U* curve in Fig. 3 is given, the average current density acquired a value of $9\cdot10^4$ A/cm^2, after which the sample collapsed.

We relate the results obtained to the intense Joule heating of the SSDI samples by the current flowing in them. To confirm this fact, it was necessary to determine the temperature of this heating.

In [2], a method for determining the temperature of a sample using its *I-U* curve was proposed. It can only be used with the onset of intrinsic conductivity $p_i \approx n_i$, where p_i and n_i are the intrinsic concentrations of holes and electrons, respectively.

Here $p_i = 7.54\cdot10^{15}T^{3/2}\exp(-6493/T)$ is the thermodynamic equilibrium concentration of electron-hole pairs in the *i*-silicon [3] (p_i and T are calculated in [cm^{-3}] and [K], respectively). The current can be determined by the formula

$$I = whep_i(T)\ \left\{v_n[E,T]+v_p[E,T]\right\}\ , \qquad (1)$$

where v_n and v_p are the electron and hole drift velocities and $E = U/l$ is the field strength. Drift velocities of electrons and holes can be defined by the empirical expressions:

$$v_n = \frac{1.42\cdot10^9T^{-2.42}E}{\left[1+\left(\dfrac{E}{1.01T^{1.55}}\right)^{2.57\cdot10^{-2}T^{0.66}}\right]^{\frac{1}{2.57\cdot10^{-2}T^{0.66}}}},$$

$$v_p = \frac{1.31\cdot10^8T^{-2.2}E}{\left[1+\left(\dfrac{E}{1.24T^{1.68}}\right)^{0.46T^{0.17}}\right]^{\frac{1}{0.46T^{0.17}}}}, \qquad (2)$$

where v_n and v_p are measured in [cm/s], T in [K], and E in [V/cm].

By the method of determining the Joule heating temperature of the sample proposed in [2], the temperature T_i of the occurrence of the intrinsic conductivity was determined (letter i in Fig. 3 marks the point where in accordance with our calculations the intrinsic conductivity occurs). Its value was 860 K. The initial concentration of charge carriers in SOI structures was $5\cdot10^{15}$ cm^{-3}, therefore it is natural that the intrinsic conductivity in them occurs at a much lower temperature $T_i = 640$ K [2].

Yellowish-white light emerges from the high-field area near the drain [7], as in SOI FET. Its appearance and extinction, as in SOI [4], indicate slight Joule heating. The flow of current in the structure is homogeneous, the current density at the same time is $2\cdot10^4$ A/cm^2, the heating led to the onset of intrinsic conductivity and the emergence of electron-hole plasma (Fig. 3).

For other characteristic points of the *I-U* curve, the calculated values of temperature are shown in Fig. 3. It should be noted that the method proposed in [2] can only be used for homogeneous current flow. The presence of S-shaped sections of the *I-U* curve indicates the formation of cords in electron-hole plasma.

Current cord occurs if the *I-U* curve of a material deviates so much from Ohm's law that it has an S-shape. The appearance of cords is characteristic of materials whose electrical conductivity increases rapidly with increasing temperature due to an increase in the concentration of charge carriers, semiconductors in particular. Heating due to Joule heat leads to an increase in conductivity and an abnormal increase in current. The current density in the cord is much higher than the density in the surrounding volume, so it may turn out that almost all the current flows through the cord [10]. This means that if the total current flows over a much smaller cross-section of the sample, the actual temperature in the cord is significantly higher.

According to the photos, the diameters of the cords were estimated, considering that the diameters of their cross-section coincide with the transverse size of the red spot. Considering that all the current flows only in the cord, then its density can be considered constant in it. Under these conditions, it was possible to determine the heating temperature directly in the cord by the method [2]. To estimate the current density, we used the formula $j = I/ka$, where k is the number of cords (red spots), a is the cross-sectional area of the cord. The current densities and the heating temperatures of the cord thus estimated are shown in Fig. 3 near the corresponding points.

Diminishing the spots size with increasing their number is also a confirmation of the formation of current cords. With each regular increase in the number of spots, the total current changes insignificantly, but only redistributes between the cords. Quantitative differences for other structures are explained by the difference in geometric dimensions, which does not affect the qualitative picture of the observed light emission.

The smaller values of average current density, at which glow in SSDI is observed compared to SOI, can be explained by the design features of SSDI. The SSDI "pocket" is surrounded on all sides by a layer of SiO_2 which blocks heat exchange, and the structure warms up more easily.

3. CONCLUSIONS

SSDI samples were investigated at high-density currents reaching average values up to 10^5 A/cm^2. The average specific power density reaches 0.9-3 GW/cm^3 for different samples.

The flowing high-density current heats the SSDI silicon film and causes the generation of thermal electron-hole plasma there. Red light emission appears in this plasma. It has the thermal nature. The emitting areas of the film have the shape of spots. The number of spots increases with the current growth. S-shape sections in the *I-U* curve correspond to the appearance of each new spot.

Plasma stratification and the formation of luminous spots are explained by the occurrence of current cords.

Considering that the current flows uniformly in the cord, the current densities and their temperatures were calculated. Estimated values are significantly higher than the average values.

Comparison of the obtained results with the same results for the SOI showed that the phenomenon of electron-hole plasma stratification and its glow may occur in any silicon structures. This should be taken into account in the manufacture of high power microelectronic devices.

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Випромінювання світла з кремнієвих структур з діелектричною ізоляцією

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В роботі представлено результати експериментального дослідження залежності струму зразків кремнієвих структур з діелектричною ізоляцією (SSDI) від напруги та описані особливості протікання струмів екстремально великої густини у структурах. Проведено дослідження процесів самоорганізації електронно-діркової плазми в SSDI, виготовлених за технологією SDI та проаналізовано отримані результати. Експериментально була визначена температура T_i виникнення власної провідності, що становила 860 K, при густині струму менше ніж $2\cdot10^4$ A/cm^2, що в порівнянні перевищує температуру в структурах, виготовлених за технологією “кремній на ізоляторі” (SOI), більш ніж на 200 K. Показано, що струм викликає інтенсивний джоулів розігрів структур, виникнення у них власної провідності та утворення електронно-діркової плазми. Розшарування плазми супроводжується світінням у вигляді симетрично розташованих червоних плям. Виникнення кожної нової плями супроводжується утворенням S-подібної ділянки на вольт-амперній характеристиці, що є типовим проявом утворення шнура струму. Струмовий шнур виникає, якщо характеристика залежності струму від напруги (*I-U*) структур SSDI настільки відхиляється від закону Ома, що має *S*-подібну форму. Зовнішній вигляд шнурів характерний для матеріалів, зокрема напівпровідників, електропровідність яких швидко збільшується зі зростанням температури через збільшення концентрації носіїв заряду. Проаналізовано отримані результати на структурах SSDI і результати досліджень випромінювання світла із структур, виготовлених за технологією SOI, що були виконані авторами раніше. З’ясовано, що ефекти в структурах SOI виникають при більш низьких значеннях густини струму.

Ключові слова: Кремнієва структура з діелектричною ізоляцією, Струми екстремально великої густини, Джоулів розігрів, Випромінювання світла.