

DEFINITIONS OF LOCALIZED ENERGY STATES ON THE QUASI-FERMI LEVEL WITH CHANGING TIMES

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Studies of the generation-recombination process of electrons from the filled localized surface states at the time of their lives. The applicability of the derivative of the Dirac distribution as δ -function at low temperatures in order to study the temperature dependence of the spectrum of the density of surface states. To improve the accuracy of the results in the paper, a method of discrete states spectroscopy on quasi-Fermi level with the changing times.

Keywords: low temperature localized state spectroscopy of discrete states, increasing the accuracy of the results, the discrete spectrum of the density of states.

ОПРЕДЕЛЕНИЕ ЛОКАЛИЗОВАННЫХ ЭНЕРГЕТИЧЕСКИХ СОСТОЯНИЙ ПО КВАЗИУРОВНЯМ ФЕРМИ С ИЗМЕНЕНИЕМ ВРЕМЕНИ

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Исследован генерационно-рекомбинационный процесс электронов из заполненных локализованных поверхностных состояний по их времени жизни. Показана применимость производной функции распределения Дирака как δ -функции при низких температурах для исследования температурной зависимости спектра плотности поверхностных состояний. С целью повышения точности получаемых результатов в работе предложен метод спектроскопии дискретных состояний по квазиуровням Ферми с изменением времени.

Ключевые слова: низкотемпературное локализованное состояние, спектроскопия дискретных состояний, повышение точности результатов, дискретный спектр плотности состояний.

ВИЗНАЧЕННЯ ЛОКАЛІЗОВАНИХ ЕНЕРГЕТИЧНИХ СТАНІВ ЗА КВАЗІРІВНЯМИ ФЕРМІ ЗІ ЗМІНЮВАННЯМ ЧАСУ

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Досліджено генераційно-рекомбінаційний процес електронів із заповнених локалізованих поверхневих станів за часом їх життя. Показано застосовність похідної функції розподілу Дірака як δ -функції за низьких температур для дослідження температурної залежності спектру густини поверхневих станів. З метою підвищення точності одержаних результатів у роботі запропоновано метод спектроскопії дискретних станів за квазірівнями Фермі зі змінюванням часу.

Ключові слова: низькотемпературний локалізований стан, спектроскопія дискретних станів, підвищення точності результатів, дискретний спектр щільності станів.

INTRODUCTION

Standard relaxation spectroscopy density of surface states is based on the generation of thermal electrons, which can be easily observed only at high temperatures. This and the limited resolution of the method. To improve the resolution of the used method of expanding the range of density of surface states in a row, the derivative of the ionization of an electron from the surface level of energy [1–3].

$$N_{ss}(E) = \sum_{i=1}^n N_{ss_i}(E_i) \frac{\partial \rho_i(E, t)}{\partial E_0(T, t)}, \quad (1)$$

where $\rho(E) = 1 - \exp\left(-\frac{t}{\tau}\right)$ [4] τ – the electron lifetime in the place he used the relation

$$\tau(E, T, t) = \tau_0 \exp\left(\frac{E}{kT}\right). \quad (2)$$

As a result, it was found that when

$$\frac{\partial \rho(E, T, t)}{\partial E_0} = \delta(E - E_0). \quad (3)$$

The resulting delta function is asymmetric, so in this situation, it took into account the additional requirements [5].

The purpose of this paper to show the suitability of the derivative of the Fermi-Dirac distribution for quasi-Fermi level from time to time as a delta function for the discrete spectrum of the density of surface states and thus increase the resolution of the method.

QUASI-FERMI TIME

The density of surface states can be determined from the loss of charge in a charge-coupled device [1, 2]. At time $t = 0$ from the surface layer completely go all the free electrons. After starting generation of thermal trapped electrons. Given the statistics of the Shockley-Read-Hall process can be described as follows [1, 2, 4]:

$$\text{and } \rho(t, \tau) = 1 - \exp(-t/\tau), \quad (4)$$

$$\text{where } \tau = 1/\gamma_n N_c \quad (5)$$

electron lifetime. Equation (4) can be represented as follows:

$$\rho(t, \tau) = 1 - \exp\left(-\exp\left(\frac{kT \ln(t) - kT \ln(\tau)}{kT}\right)\right). \quad (6)$$

If we consider that in this process each time the surface layer is cleaned from the released electrons generated from the traps, the changes over time energy of the Fermi level E_{ft} . In the future, this value depends on the time t is denoted as the quasi-Fermi level.

We introduce the notation:

$$E_\tau = kT \ln(\tau) \quad (7)$$

electron energy of the lifetime τ and

$$E_{ft} = kT \ln(t) \quad (8)$$

quasi-Fermi energy by the time t .

Considering (7) and (8) may be (6) in the form:

$$\rho(E_{ft}, E_\tau) = 1 - \exp\left(-\exp\left(\frac{E_{ft} - E_\tau}{kT}\right)\right). \quad (9)$$

One can easily imagine the derivative $\rho(E_{ft}, E_\tau)$ on E_{ft} as a delta function at $T \rightarrow 0$

$$\frac{\partial \rho(E_{ft}, E_\tau)}{\partial E_{ft}} = \delta(E_{ft}, E_\tau). \quad (10)$$

SPECTROSCOPY OF QUASI-FERMI CHANGE IN TIME

The distributions function of the Fermi-Dirac distribution for the generation of electrons:

$$f = \left[\exp\left(\frac{E_{ft} - E_\tau}{kT}\right) + 1 \right]^{-1} \quad (11)$$

step function is known energy [6]. It is also known that the derivative of the energy function of speed is the Dirac delta function (see fig. 1) in $T \rightarrow 0$ [6]. In this case, the delta function is as follows:

$$f = \frac{1}{kT} \exp\left(\frac{E_{ft} - E_\tau}{kT}\right) \left[\exp\left(\frac{E_{ft} - E_\tau}{kT}\right) + 1 \right]^{-2}. \quad (12)$$

The resulting function (12) we substitute in (1) and get:

$$N_{SS}(E) = \sum_{i=1}^n N_{SS_i}(E_i) \frac{1}{kT} \exp\left(\frac{E_{fti} - E_\tau}{kT}\right) \times \left[\exp\left(\frac{E_{fti} - E_\tau}{kT}\right) + 1 \right]^{-2}. \quad (13)$$

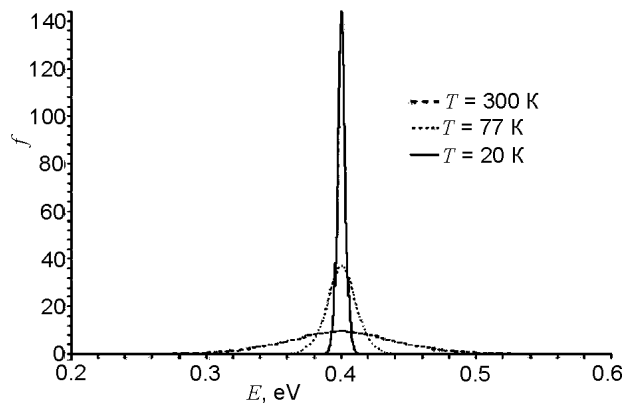


Fig. 1. The derivative of a step function at the Fermi-Dirac distribution of energy at different temperatures.

If we imagine that the quasi-Fermi E_{ft} level changes throughout the segment gap in each relevant electron energy E_τ generated from the trap life time τ , we get a peak delta function. Scanning energy E_{ft} for each specific temperature, perhaps because it is theoretically possible to set the appropriate time τ $E_{ft} \in [E_c, E_v]$. Fig. 2 shows a range where the shaded area are 10 discrete levels at different temperatures. It is easy to notice that for the discrete spectrum as in [1–4], we can use the derivative of the Fermi-Dirac distribution on E_{ft} a delta function.

TEMPERATURE DEPENDENCE OF THE DENSITY OF SURFACE STATES AND DISCRETE SPECTRA

We turn to the treatment of the density of surface states. Fig. 3 shows the density of surface states of [7], which shows the graphs of experimental and theoretical fitting the density of states $N_{SS}(E, T)$

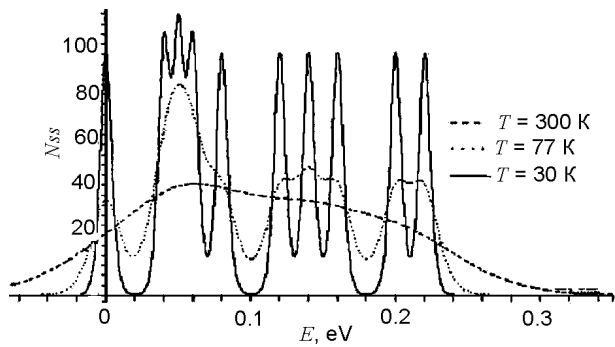


Fig. 2. The spectrum of the density of surface states at different temperatures.

obtained by the decomposition of the experimental curve in a series of functions (12).

Analysis of fig. 3 $N_{ss}(E, T)$ shows that the experimental plot at $T=300$ K is easily decomposed into a series of functions (12). Fig. 4 is a graph theoretical model density of states that for $T=5$ K. From these figures one can see that even at a low temperature in the graph clearly distinguish the individual peaks.

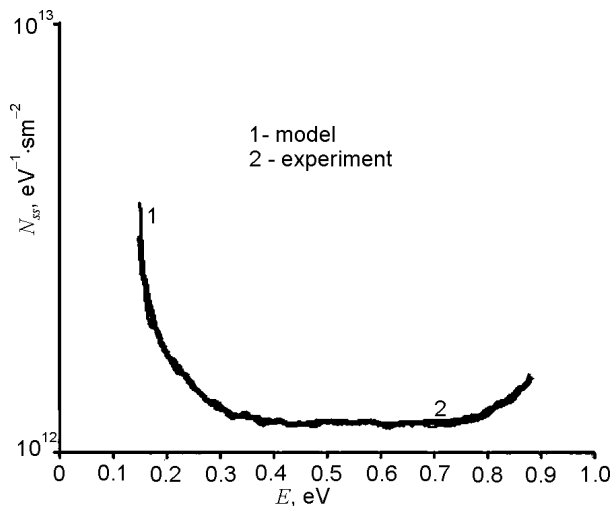


Fig. 3. Experimental [7] and the model spectrum density of surface states at $T=300$ K.

When the temperature tends to zero, these peaks are transformed into discrete levels, and the continuous line $N_{ss}(E, T)$ in the discrete energy spectrum (see fig. 4). These changes $N_{ss}(E, T)$ are due to the fact that the temperature is lowered by reducing the thermal broadening of the energy levels (12) becomes the Dirac delta function $\delta(E - E_0)$.

Based on the study, it can be concluded that the experimental continuous spectrum density of surface states $N_{ss}(E, T)$ at a certain high temperature relaxation method at low temperatures becomes a discrete energy spectrum. Such a strong temperature dependence of the density of surface states due to

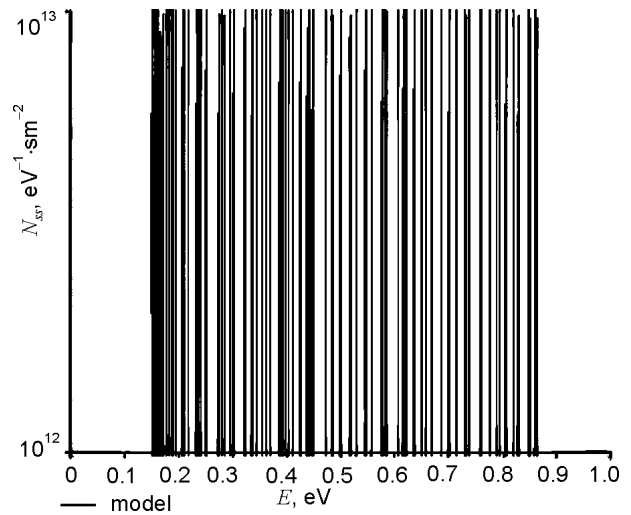


Fig. 4. Model discrete spectrum of the density of surface states at $T=5$ K.

the fact that the derivative of the Fermi-Dirac distribution becomes a Dirac delta function.

The present method of determining the density of the surface low-temperature conditions increases the resolution of the transient spectroscopy and surface levels of relaxation techniques used to measure the energy spectrum of the density of states.

CONCLUSION

According to the study of surface electrons recharge levels in their lifetime based on the principle of CCD determined that the derivative of the ionization energy of the electron is a r -function at $T \rightarrow 0$. The applicability of the derivative of the Dirac distribution function of the energy of the quasi-Fermi level with the time change as a δ -function at low temperatures in order to study the temperature dependence of the spectrum of the density of surface states. This was possible because the derivative of a step function is a δ -function. We propose a method of spectroscopy of discrete states by quasi-Fermi level with the change of time to improve the accuracy of the results.

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