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Abstract.

Abnormal dependence of volt-farad characteristics of «nonideal» heterojunction barrier capacity is investigated. It is shown that in heterojunctions with the big concentration and non-uniform distribution of defects tunnel currents essentially influence on the barrier capacity size.

The model for an explanation of abnormal barrier capacity dependence on the voltage, using tunneling-recombination mechanism of carriers carry through the area of a spatial charge is offered. The put forward assumptions put in a model basis, are confirmed experimentally.

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ОСОБЛИВОСТІ ВОЛЬТ-ФАРАДНОЇ ЗАЛЕЖНОСТІ БАР’ЄРНОЇ ЄМНОСТІ НЕІДЕАЛЬНИХ ГЕТЕРОПЕРЕХОДІВ

Резюме

Досліджено аномальну залежність вольт-фарадної характеристики бар’єрної ємності «неідеальних» гетеропереходів. Показано що в гетеропереходах з великою концентрацією і неоднорідним розподілом дефектів тунельні струми істотно впливають на величину бар’єрної ємності.

Запропоновано модель для пояснення аномальної залежності бар’єрної ємності від напруги, що використовує тунельно-рекомбінаційний механізм переносу носіїв через область просторового заряду. Висунуті припущення, покладені в основу моделі, підтверджені експериментально.

Ключеві слова: неідеальний гетероперехід, вольт-фарадна характеристика, стрибкова провідність

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Резюме

Исследована аномальная зависимость вольт-фарадной характеристики барьерной емкости «неидеальных» гетеропереходов. Показано что в гетеропереходах с большой концентрацией и неоднородным распределением дефектов туннельные токи существенно влияют на величину барьерной емкости.

Предложена модель для объяснения аномальной зависимости барьерной емкости от напряжения, использующая туннельно-рекомбинационный механизм переноса носителей через область пространственного заряда. Выдвинутые предположения, положенные в основу модели, подтверждены экспериментально.

Ключевые слова: неидеальный гетеропереход, вольт-фарадная характеристика, прыжковая проводимость

At selection of semiconductor substances for heterojunction (HJ) creation the semiconductor “ideal” pairs are considered those which crystal lattices constants differ on the tenth part of percent. However at the majority of the semiconductor compounds suitable to manufacturing HJ with necessary properties, crystal lattices constants differ in some percents. Such lattices discrepancy creates on the interface high density of states (~ 10^{14} sm^2) [15], being the centres through which recombination and tunneling can be carried out. These phenomena usually degrade the HJ work, nevertheless some “nonideal” heteropairs are perspective. Classical type of “nonideal” HJ is pair CdS - Cu_2S, used as a photo cell with efficiency of 7... 9 %.

In the present work cadmium sulfide – cupper sulfide HJ, received in a aninted vacuum cycle on a glass substrate with the transparent SnO_2 conducting layer were investigated. The technology of HJ obtaining is based on consecutive thermal evaporation of cadmium sulfide and copper chloride in vacuum.

Formation of heterojunction CdS-Cu_2S occurs as a result of solid-state substitution reaction by ions Cu^{+} ions Cd^{2+} on a surface of cadmium sulfide at heating of the CdS-CuCl structure in vacuum [2].

Crystal lattices constants of CdS and Cu_2S differ on 4 % [3] that is the reason of occurrence of the big concentration of mismatch dislocation which can serve as centres of recombination, and also centres of capture for holes and electrons. These centres play the important role in processes of current transport and charges separation and are located in the spatial charge region (SCR), completely laying in volume of cadmium sulfide, because of heterojunction asymmetry.

Data on these centre parameters and on donor concentration distribution in SCR can be received, by investigating the barrier capacity dependences on voltage. Measurement of volt-farad characteristics of “nonideal” HJ usually gives in coordinates C^{-2}...U a straight line with one or several breaks (fig. 1, curve α). These sections testify the presence of areas with various charge concentration amounts in SCR [1].

For CdS-Cu_2S heterojunctions, received on the described technology, volt-farad characteristic had more complex character shown in abnormal behaviour of curve C^{-2}...U dependence at small negative and positive voltages (fig. 1, curve *b*).

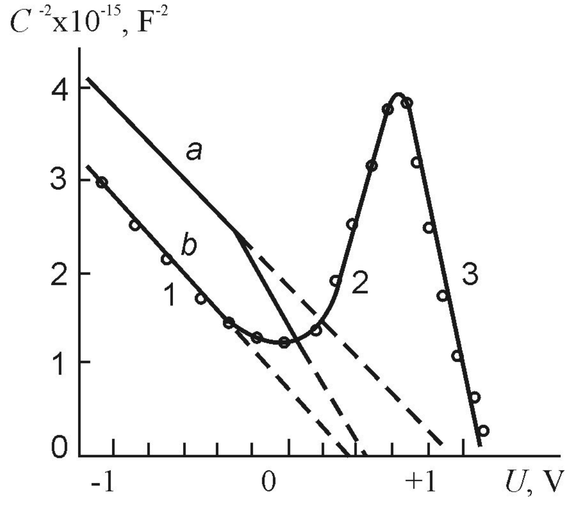

Fig. 1. Dependence of C^{-2} amount on a voltage for heterojunction with the step distribution of charge concentration in base: a - theoretical dependence; b - experimental curve

Presence of two linear sections 1 and 3 on the experimental curve is connected to existence of two layers with various charge carrier concentrations. These layer extents L_1 and L_2 were calculated under the formula:

$$L_{1,2} = \left[\frac{2\varepsilon\varepsilon_0 \left(\varphi - eU \right)}{e^2 N_{1,2}} \right]^{\frac{1}{2}}$$

Where ε_0 - absolute dielectric permeability; ε - relative dielectric permeability of of cadmium sulfide; e - electron charge; U - the voltage biased to heterojunction; φ - the barrier height determined on a cut-off voltage: φ_1 = 0,27 eV, φ_2 = 1,05 eV. Concentration of a charge in layers is determined by expression

$$N_{1,2} = \frac{2}{\varepsilon\varepsilon_0 e S^2}\left[\frac{d\left(C^{-2}\right)}{dU}\right]^{-1}$$

where S – HJ area.

For layer L_1 = 0,51 microns, $N_1 = 4,1\cdot 10^{15}$ cm^{-3}. For layer L_2 = 0,12 microns, $N_2=2,2\cdot 10^{16}$cm^{-3}. Smaller values of concentration N_1 of boundary layer L_1 are connected to copper diffusion into cadmium sulfide volume at heterojunction formation. Copper atoms are acceptors in cadmium sulfide and, lower the charge density by compensating donor centres.

On fig. 2 the band diagram constructed on calculated values N_1, N_2 and L_1, L_2 is given. However, such model allows to explain only volt-farad dependence submitted by the curve *a* on fig. 1.

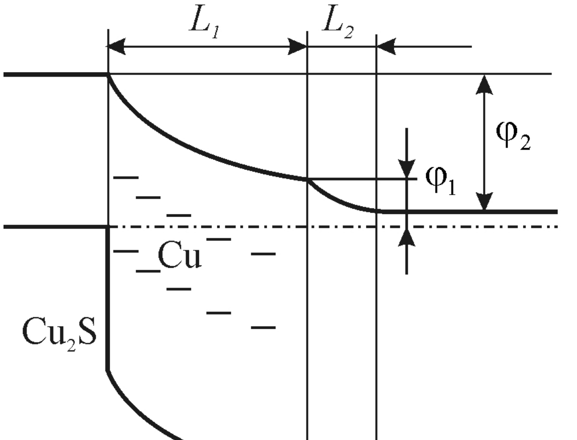

Fig. 2. The band diagram of heterojunction, constructed on the data of the experimental volt-farad dependence

As it is obvious from fig. 1 (curve *b*), the experimental curve has an abnormal section on which the capacity grows with reduction of a direct voltage. The behaviour of the volt-farad dependence curve on a section 2 does not find an explanation within the framework of model [1].

The observable trend of curve can be the consequence of a field devastation of the electronic capture levels located in volume of cadmium sulfide near to HJ border. Intensity of an electric field necessary for this process is realized in SCR at negative and small positive biases. The competition of the deep electronic traps filling processes and their full devastation results in increase or reduction of SCR width. Change of the barrier capacity amount in this case should be accompanied by a current relaxation at change of bias polarity. However the experiment which has been carried out in a wide range of frequencies, has not found out current relaxation that does not allow using the described mechanism.

For interpretation of abnormal course experimental volt-farad characteristics the assumption that conductivity G_1 of layer L_1 is much more than conductivity G_2 of layer L_2 is made. The assumption is made contrary to inequalities: $L_1 > L_2$, $n_1 < n_2$, however is justified as conductivity in barrier areas of nonideal HJ can be connected to the tunnel mechanism.

For more information on the current transport mechanism temperature dependences of heterojunction conductivity were investigated. Temperature dependence of samples conductivity at positive bias on junction in an interval of temperatures from nitrogen up to room is badly straightened in $lnG...T^{-1}$ coordinates. The average amount of activation energy, determined on the specified dependence, is equal 0,012 eV. However the measured temperature dependence is well straightened in $G...T^{-1/4}$ coordinates. According to Mott-Devis theory [6] such dependence observing in homogeneously - disorderly semiconductor substance what the area of heterojunction CdS-Cu_2S spatial charge is, and also the abnormal low energy of thermal activation of conductivity, specify on jumping mechanism of current transport on local states. This is specified with observing frequency dependence of active component of conductivity $G...\omega^{0,8}$ in a range of frequencies $5 < \omega\cdot < 200$ kHz.

Conductivity of barrier areas of researched samples in the greater degree is determined by a tunnel transparency, than the carrier concentration. At cupper diffusion into CdS boundary layer arise a plenty of failures of a crystal lattice that provides multistage process of tunneling through rather extended area L_1 [7].

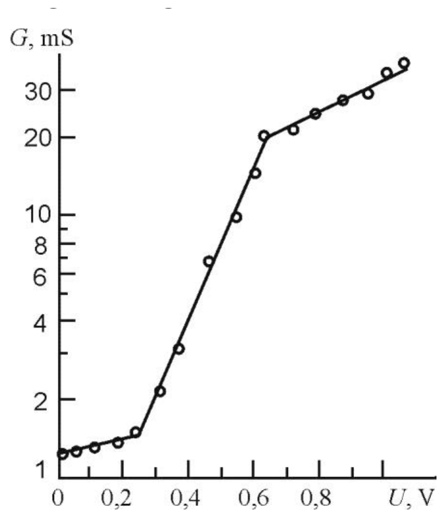

Fig. 3. Dependence of dark conductivity on positive bias on heterojunction (frequency of a measuring signal is equal 10 kHz)

HJ capacity, measured experimentally, is connected to a layer of the lowest electroconductivity. At negative bias on junction when SCR has the big extent, and at performance of inequality $G_1 >> G_2$, the capacity of only layer L_2 is measured, and layer L_1 is perceived by the measuring device as series connection resistance.

At the apply on HJ positive bias thickness of L_2 layer decreases and it should result in increase of measured capacity. Simultaneously there is a redistribution of measuring signal voltage: it grows on L_1 and decreases on L_2.

Under these conditions, the capacity of both layers is measured and the abnormal behavior of volt-farad dependence is observed. Reduction of capacity proceeds until SCR does not become equal to layer L_1 thickness. At the further increase of positive bias capacity SCR, laying only in layer L_1 is measured, as now this area has the lowest conduction. In these conditions, the normal section of volt-farad characteristic is again observed.

The confirmation of the offered model is the measured dependence *G=f(U)* submitted in fig. 3. Really, at the voltages appropriate to an abnormal section of a curve $C^{-2} = f(U)$ and to redistribution of decline in potential between areas L_2 and L_1. sharp increase of heterojunction electroconductivity is observed.

It is typical for the given band diagram, that he position of L_1 border has "biographic" character while the width of L_2 layer depends on the bias voltage or other influences. At excitation of heterojunction by light the space charge region has smaller extent as a result of the capture level filling by photoexcited holes [4]. In such conditions at zero bias on heterojunction the space charge region is placed only in the compensated layer, characterized, as it was shown above, by tunnel-recombination mechanism of conductivity.

Thus, on the example of classical nonideal structure on the basis of semiconductor compounds cadmium sulfide – cupper sulfide it is shown, that in heterojunctions with the big concentration and non-uniform distribution of defects in boundary region tunnel currents essentially change dependence of barrier capacity on a voltage.

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