THE DETERMINATION OF THE NATURE OF DEEP LEVELS IN SILICON *p-n* JUNCTIONS

S.G. RZAYEV, Z.M. ZAKHRABEKOVA
Institute of Physics of the Azerbaijan National Academy of Sciences
H. Javid av. 33, Baku, 370143

Dependences of the deep levels (d.l.) recharging time constant on the temperature (T) are determined by methods of the deep levels transient spectroscopy (DLTS). The nature of d.l. in p-n junction of silicon integrated circuits is revealed without destroying their structures.

Deep levels in the forbidden band of semiconductors have the considerable influence on parameters of semiconductor devices, in particular, they determine such important parameters of p-n junctions, as the leakage current, breakdown voltage, the carriers lifetime, etc. It is necessary to reveal the nature and carry out more detailed research of their properties and determination of parameters for working out the model notion about their influence mechanism on electron processes in semiconductors.

Methods of thermostimulated currents (TSC) shown to be rather effective at the same time are simple research methods. Parameters of d.l. in silicon planar p-n junction have been revealed and determined in [1] with the help of these methods. Though they allow to reveal and estimate d.l. parameters these methods are insufficient for determination of their nature. Therefore it is necessary to search for methods allowing to determine the nature and to define d.l. parameters in p-n junctions more precisely. Methods of DLTS have such properties. They are distinguished by the high sensitivity and resolvability capacity and also by the simplicity of the results interpretation, what is particularly important for the determination of the d.l. nature.

In the present work d.l. in p-n junctions of integrated circuits (IC) of the high integration are revealed and studied by methods of DLTS and on the base of this study before unknown nature of d.l. is revealed and their parameters are determined more precisely.

Methods of the experiment and a discussion of results

Research has been carried out on planar silicon p-n junctions, whose section is represented in [2]. The basic region of the junction consists of the part of the epitaxial film of the (111)-surface of the ≈2.1mkm thickness alloyed by boron ($\approx 5\cdot 10^{16}$cm^{-3}). The collector region consists of the n-layer, formed in the p-substrate of the As (10^{20}cm^{-3}) diffusion, and the vertical n – layer attached to it created in the epitaxial film by the phosphorous ($\approx 5\cdot 10^{18}$cm^{-3}) diffusion, which exits to the film surface.

Deep levels were revealed in studied p-n junctions of high leakage currents by TSC methods and their parameters were determined: the activation energy is E_t=(0.24±0.003)eV, a section of capture is σ=(3÷5)$\cdot 10^{-20}$cm^2, the d.l. concentration is Nt= (1÷5)$\cdot 10^{16}$cm^{-3} [1].

Although the TSC method is very informatic and technically simple, it has a number of shortcomings, one of them is the impossibility of the simultaneous determination of σ and N_t. Another essential shortcoming of this method is the fact, that parameters of d.l. are calculated by the form and peaks position of TSC on the temperature scale, on which the rate of the sample heating, the degree of the initial centers filling and the value, attached to the sample the electric field, have the noticeable influence. Therefore, as a rule, the other independent method is applied at the use of TSC method for the check of obtained results and the receipt of the additional information. The method of DLTS is applied as the control method in the present work, which allows to determine σ and N_t simultaneously and also to find the dependence of the d.l. recharging time on the temperature, what is particularly important for the determination of the d.l. nature, as it will be shown below.

The main point of the DLTS method consists of the following:

This method is the particular case of the capacitance spectroscopy, based on the measurement of capacity changes of p-n structures, caused by the recharging of d.l. in the space charge layer. If the inverse bias is given to p-n junction, then all free carriers (in given case electrons) for the time of 10^{-10}s order will escape the space charge layer (SCL) to the region of the electrical neutrality and capture processes on d.l. will be practically excluded in the region of the SCL; i.e. processes of the carriers emission from the level will dominate, that leads to the change of the charged centers concentration in the SCL.

If the inverse bias is removed, the electrons will return to the depletion region and the process of their capture on the d.l. will start. If holes are introduced in the studied region with the previously filled centers, then the process of their capture will be dominating. And, at last, if centers are devastated and all free carriers are removed from the depletion region, then the process of the holes emission from d.l. will dominate. As it is seen from above-mentioned, variating the bias voltage, given to p-n junction, the conditions may be created, under which the charge of the ionized centers concentration in the SCL will be determined by a single process. The change of the ionized centers concentration in the SCL is externally manifested through the capacity change. The d.l. recharging occurs with some time constant, which exponentially depends on the energy activation E_t of the level and on the temperature T [3]:

$$\tau_{r.c} = (\sigma_n \vartheta_T N_c)^{-1} exp\left(\frac{E_c - E_t}{KT}\right) \qquad (1)$$

where σ_n is the cross section of the electron capture on the d.l., ϑ_T is the heat velocity of the electron, N_c is the state density in the conduction band.

The relation between the capacity charge, the d.l. concentration and the constant of the recharging time is determined from the Poisson equation:

$$div\overline{E} = \frac{\rho}{\varepsilon_0 \varepsilon_s} \quad (2)$$

where $\overline{E}$ is the electric field strength, ρ is the charge density, ε_s is the dielectric constant of the semiconductor. The particular solution of this equation is given in [3,4]. Both the constant of the recharging time of the d.l. and the section of the carriers capture may be determined by the choice of the experiment conditions, and the energy activation of the d.l. may be determined by the slope of $ln(\tau T^2) \sim 1/T$ dependence from [1]

It follows from [1], that the recharging time constant of the d.l. depends on both the activation energy and the carriers capture cross-section. The $\tau(T)$ dependences are different for two d.l. with the identical activation energy in the consequence of this. This dependence is applied as the main distinctive sigh of the impurity. The unknown d.l. is identified by the coincidence of the (T) dependence for all levels with corresponding dependences for one of known impurities.

Two methods of DLTS are distinguished depending on the measured quantity:

1. The constant voltage when the capacity transient is measured at the constant bias voltage in p-n junction.
2. The constant capacity when the capacity of the *p-n* junction is supported by the constant, and the change of the bias voltage, backing the capacity constant, is measured.

The capacity, the width of the SCL and the concentration of ionized d.l. are changed depending on the time in the case of the constant voltage (the capacity transient), what makes the measurement of d.l. parameters difficult in the case of the heterogeneous distribution of shallow and deep levels in the semiconductor volume. The method of the capacity constant (the voltage transient) where not changes of the barrier capacity in the time are registered, but the voltage change, lacks this shortcoming.

The compensated method, in which the tracking system automatically compensates the capacity change in the time, is caused by the d.l. ionization by the means of the supply of small compensated increments of the voltage on the sample, is the most convenient from different registration methods of voltage changes. The mentioned method allows to unite the transient filtration with the defined time constant and to support the capacity constant in the time. This method allows to measure the quick voltage transient ($\tau = 10^{-6} \div 10^{-1}$s).

The principal scheme of the device, on which the compensated registration method of voltage changes is realized on the barrier, is shown on fig.1. The description and its advantages over other capacity research methods of d.l. are shown in [4,5].

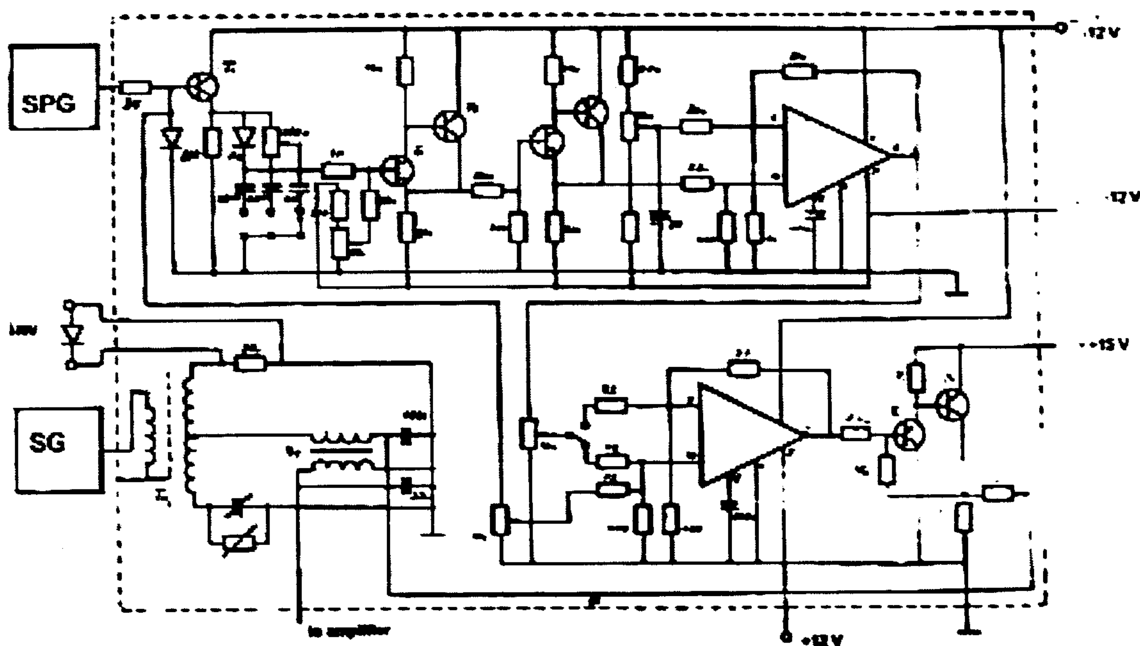

Fig.1 The principal scheme of the compensated device for the transient registration of the voltage on the *p-n* junction.

The regulating voltage during changes with the time changes according to the exponential law at the d.l. recharge:

$$u(t) = u_0 exp(-t/\tau_{r.c.}) \quad (3)$$

where $u_0 = q/\varepsilon \int_0^{x-\lambda} N_t x dx$, x is the thickness of the depletion region, $\lambda = \sqrt{2\varepsilon(E_F - E_t)/q^2 N_s}$; N_s is the concentration of shallow impurities, q is the electron charge, exponential impulses (EI) of the voltage $u = u_{EI}\ exp(-t/\tau_{EI})$ with the fixed time constant τ_{EI} are synchronously delivered on samples along with the rectangular impulses of the inverse bias and it is necessary to fulfill the conditions $u_o = u_{EI}$, in order that the diode capacity remains constant in the recharging process at $\tau_{r.c.} = \tau_{EI}$.

The fulfillment of these conditions is provided by the fact, that the EI amplitude is persistently regulated by the slow feed-back, keeping the bias at minimum.

As it has been noted above, the constant of the recharging time changes with the temperature change according to the law (1). The value $\tau_{r.c.}$ is determined by the condition, that each extremum on τ_{EI} *(T)* dependences corresponds to the d.l., possessing by the recharge time $\tau_{r.c}$ at the given temperature.

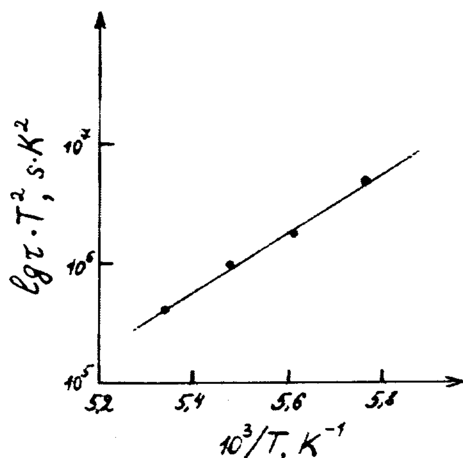

Fig. 2 Dependence of $lg(\tau T^2) \sim 1/T$ for p-n junctions with deep levels.

Therefore, the d.l. spectrum in the forbidden band may be determined from [1] at the smooth change of the temperature.

The Arrenius dependence $lg(\tau T^2) \sim 1/T$ for the *p-n* junction with high leakage current is shown on fig.2. D.l. have been earlier revealed by us by TSC methods in these samples and it has been established, that they increase the leakage current in $10^2 \div 10^3$ times, and also reduce the breakdown voltage in 0.4V in [1,6,7]. However, the nature of d.l. has remained obscure.

The main parameters of revealed d.l. have been determined by the analysis of the obtained Arrenius dependence (fig.2), using formula (1).

The activation energy is E_t=0.24eV, the capture cross-section is σ=3.5 $\cdot 10^{-20}$cm^2, the emission coefficient is e_n =1.2$\cdot 10^2$e^{-1} K^{-2}, the d.l. concentration is $(1 \div 5) \cdot 0^{16}$cm^{-3}, the capture coefficient is γ=5$\cdot 10^{-14}$cm$^{-3} \cdot$s^{-1}. Obtained values completely agree with values of appropriated parameters, obtained by TSC methods. It witnesses the reliability of the obtained results.

The analysis of the *(T)* dependence and also parameters for d.l. of the activation energy E_t=0.24eV has shown, that they coincide with analogous parameters for impurity atoms of the copper in the silicon [8,9]; i.e. revealed d.l. are caused by atoms of the copper. The quartz, applied in industrial devices, may serve as the possible pollution source of the serial IC.

Conclusion

Thus, applying the suggested method of $\tau(T)$ determination in the given work, the d.l. parameters may be exactly determined by DLTS methods and the identification may be carried out with parameters of known impurities without destroying *p-n* structures.

Obtained data may be applied for more accurate definition of model notions about the d.l. influence on electron processes in semiconductors, and also for the correction of the technological production process of semiconductor devices.

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S.Q. Rzayev, Z.M. Zöhrabəyova

SİLİSİUM *p-n* KEÇİDLƏRİNDƏ DƏRİN SƏVİYYƏLƏRİN TƏBİƏTİNİN TƏYİN EDİLMƏSİ

Dərin səviyyələrin (d.s) yük dəyişməsinin zaman sabitinin temperaturdan asılılığının d.s. relaksion spektroskopiya (DSRS) metodu ilə təyin etmənin üsulu verilib. Bu üsul ilə silisium inteqral sxemlərin *p-n* keçidlərində d.s. təbiəti təyin edilib və onların mis atomlarına aid olduğu təsbid edilib.

С. Г. Рзаев, З. М. Захрабекова

ВЫЯСНЕНИЕ ПРИРОДЫ ГЛУБОКИХ УРОВНЕЙ В КРЕМНИЕВЫХ *p-n* ПЕРЕХОДАХ

Методами релаксационной спектроскопии глубоких уровней (РСГУ) определены зависимости постоянной времени перезарядки глубоких уровней от температуры $\tau(T)$. Выяснена природа глубоких уровней в p-n переходах кремниевых интегральных схем, не разрушая их структуры.

Received: 11.10.01