INFLUENCE OF PULSE LASER IRRADIATION ON THE DETECTING PROPERTIES OF Pt—p-CdTe:Cl CONTACTS WITH A SCHOTTKY BARRIER

P.M. GORLEY, O.I. VOROBETS, G.I. VOROBETS,
K.S. ULYANYTSKYI, V.V. HOMYAK

Yuri Fedkovych Chernivtsi National University
(2, Kotsyubynskyi Str., Chernivtsi 58012, Ukraine; e-mail: vgeorge@chnu.cv.ua)

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The physical mechanisms of the influence of the millisecond pulse laser irradiation with subthreshold intensity on the formation of the interface layer in Schottky diodes (SDs) Pt—p-CdTe:Cl and the current flowing in them have been investigated. The procedure of exposing Pt—p-CdTe:Cl structures to laser radiation have been developed, and its optimal parameters, at which the reduction of the density of deep levels associated with impurity-induced structural defects in the semiconductor and the reduction of the generation-recombination component of the current in a SD become possible, have been found. The magnitude of the potential barrier in Pt—p-CdTe:Cl contacts, $\varphi_b = (0.84 \pm 0.02)$ eV, and the activation energies of deep levels – $E'_a = (0.58 \pm 0.02)$ eV, $E''_a = (0.72 \pm 0.02)$ eV, and $E'''_a = (0.43 \pm 0.02)$ eV — have been determined.

1. Introduction

Diodes with the Schottky barrier fabricated on the basis of semi-insulating CdTe are widely used as primary signal converters in systems for measuring the radioactive level of γ-radiation [1]. Their detecting properties are governed by features of the current flowing through the potential barrier. In most cases [1–10], the mechanism of the current flowing in the contacts metal — p-CdTe is described by the generation-recombination current caused by the presence of deep levels in the space charge region (SCR) of a SD. A satisfactory agreement between the experimental data and the theory was obtained in the framework of the Sah–Noyce–Shockley model adapted for SDs and taking into account the effect of the base region conductance modulation at the injection of minority current carriers [2]. However, impurity-induced structural defects, which create deep levels in the semiconductor, lead, as time goes by, to the contact degradation and ageing [3]. After a long exploitation of SDs under the conditions of high-energy irradiation and at critical temperatures, the rates of their degradation become accelerated.

To stabilize and correct the parameters of barrier structures, the laser irradiation (LI) of SDs with millisecond pulses is applied [4, 5]. Provided that LI modes at the metal–semiconductor contact (MSC) interface are optimal, the processes of interaction of phases in the solid state become activated. Depending on the character of physical and chemical processes of the interphase interaction between the metal and the semiconductor compound, a nano- or microstructured transition layer, whose electronic properties affect the electrophysical characteristics of detecting surface-barrier structures, is formed at the MSC interface [6].

Note that the use of LI modes with nanosecond pulses results in the local melting of the irradiated surface or in the nonequilibrium evaporation of one of the components in binary semiconductor compounds [7–12]. Such a process is hardly controllable, because it depends not only on the laser emission modes (in particular, the emission intensity I_0 [W/cm^2]) but on the state of the irradiated surface (polishing quality, the coefficients of radiation reflection and absorption, and so on).

In this work, we have developed the techniques of LI and found its optimal modes for Pt—p-CdTe:Cl structures. The physical mechanisms of the influence of the pulse laser irradiation on the formation of the transition layer and the mechanisms of the current flowing in SDs Pt—p-CdTe:Cl have also been studied.

2. Experimental Technique

The researched Pt—p-CdTe SDs were formed by sputtering platinum in vacuum onto a preliminarily polished, degreased surface of a high-resistance crystalline substrate. The specific conductance of the initial — compensated by chlorine and annealed in Cd vapors — p-CdTe crystal was $\sigma \approx 3\times10^{-9}\ \Omega^{-1}\ \text{cm}^{-1}$ and the hole mobility $\mu_p \approx 45\ \text{cm}^2/(\text{V}\times\text{s})$ at $T \approx 300$ K. The temperature of the substrate was maintained within

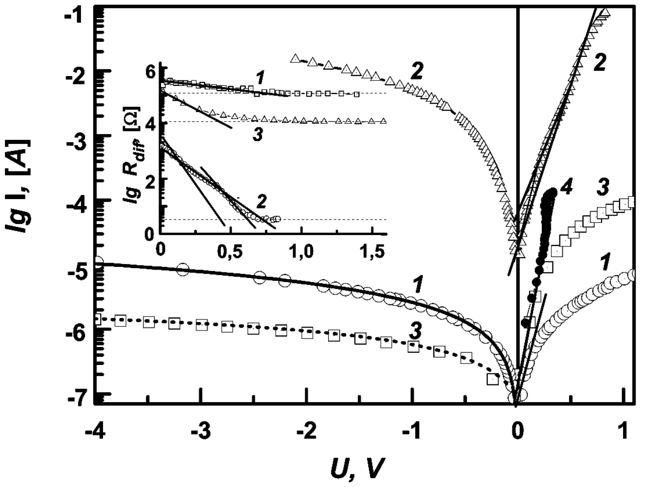

Fig. 1. Typical VACs of Schottky diodes Pt—p-CdTe:Cl: for a SD created on a high-resistance p-CdTe:Cl crystal, before (*1*) and after (*3*) LI; and for a SD created on a low-resistance p-CdTe:Cl crystal (*2*). Curve *4* is VAC *3* plotted on the $\lg I = f(U - IR_s)$ scale. The corresponding calculated $\lg R_{\rm dif} = f(V)$ dependences are depicted in the inset

the limits of 100—150 °C during sputtering; the residual pressure of air in the vacuum chamber was $p \approx 10^{-6}$ Torr. The thickness of the Pt film was 0.2—0.3 μm; the area of the rectangular contacts was $S \approx 3 \times 5$ mm^2. Ohmic contacts were obtained by chemical deposition of gold. No additional high-temperature treatment of contacts was used.

The laser irradiation of SDs was carried out in a quasiadiabatic mode in the open air. An yttrium aluminum garnet (YAG:Nd) laser that operated in the Q-switched mode was used as a source of radiation. The lasing wavelength was $\lambda = 1.06$ μm. The emission intensity was varied within the scope from several watts to 100 kW per cm^2 by changing the laser pump voltage and/or defocusing the laser beam to the diameter $d \approx 2 \div 4$ mm.

The optimal mode of the irradiation was found empirically by changing the pulse duration and the pulse-repetition frequency. The irradiation mode was monitored optically immediately in the course of irradiation and by means of metallographic studies after the irradiation procedure. The optimal regime was considered to be realized at that maximal intensity, which did not induce visible morphological modifications on the irradiated surface. It was found experimentally that the optimal LI mode for the structures under investigation is achieved when a series of 20 pulses was used, each pulse having the duration $\tau = 0.5$ s, and the pulse-repetition frequency being $f = 1$ Hz.

The influence of the laser irradiation on the detecting properties of SDs was detected by analyzing their volt-ampere (VAC) and volt-farad (VFC) characteristics.

3. Experimental Results and Their Discussion

The VACs of Schottky diodes Pt—p-CdTe, measured before and after laser irradiation, are depicted in Fig. 1. The rectification factor of initial SDs amounted to 8—15 at $U = 1$ V. The coefficient of ideality of the VAC straight line (Fig. 1, curve *1*), which was determined within its initial section 0.075 V $< U_{np} <$ 0.20 V by the formula $n = \frac{1}{\varphi_T}\frac{dU}{d\ln I}$ [6], falls within the interval from 2.62±0.02 to 2.77±0.02. Such a value of n evidences for the presence of additional currents in the SD, besides the generation-recombination one, for which $n = 2$.

The results of researches of the VAC of Pt—p-CdTe diodes fabricated following the technique described above on low-resistance crystals also testify for the existence of several mechanisms of the current flowing in SDs. This conclusion is confirmed by the fact that VACs include several linear sections with different slopes $\alpha = \frac{d\ln I}{dU}$ (Fig. 1, curve *2*), where α is the coefficient of VAC linearity on the semi-logarithmic scale [6]. However, if a semi-insulating CdTe:Cl crystal was used to produce the structure, there was an additional voltage drop across the high-resistance base of the diode [2]. It is evidenced by the forward-bias VACs plotted on the $\lg I = f(U - IR_s)$ scale, where R_s is the series resistance of the base (curve *4* and dark points in Fig. 1). The magnitude of the quantity R_s was determined on the supposition that the dependence of the differential resistance on the voltage saturates, provided that the potential barrier of the SD is completely open at a forward bias (see the inset in Fig. 1). Typical values of R_s for investigated diodes before irradiation were 1.2×10^5 Ω before and 1.1×10^4 Ω after irradiation.

The analysis of the VACs of SDs after their irradiation (Fig. 1, curve *3*) testifies that the rectification factor of such structures becomes more than two orders of magnitude as large in comparison with that of nonirradiated SDs. The forward-bias currents increase at that by a factor of 15–20, while the reverse-bias currents decrease by a factor of 10. The coefficient of ideality reduces to $n = 2.07 \pm 0.02$ ($\alpha = 19.36 \pm 0.02$), which is typical of the generation-recombination current. The VAC curves $\lg I = f(U - IR_s)$ of the Pt–p-CdTe Schottky diodes subjected to LI are characterized by the presence of two quasilinear sections with the parameter $\alpha \approx 14.54 \pm 0.02$ ($n \approx 2.76 \pm 0.02$) at low biases (0.075 V $< U \leq 0.2$ V) and $\alpha \approx 37.89 \pm 0.02$ ($n \approx 1.06 \pm 0.02$) at 0.2 V $< U < 0.4$ V. The latter value of the coefficient n is typical of the overbarrier current in the SD that is close to the ideal one. The amplitude of the potential barrier φ_b can be determined in this case from the saturation current I_s at $U = 0$, making use of the classical current-versus-voltage dependence for the forward-bias branch of the Schottky diode VAC [13]:

$$I = AT^2 S e^{-\varphi_b/\varphi_T} e^{U/\varphi_T}, \tag{1}$$

where A is the Richardson constant for a thermionic current over the barrier [6], T the absolute temperature of the contact, S the contact area, $\varphi_T = kT/q$ is the temperature potential, q the electron charge, and k the Boltzmann constant.

The value of φ_b after LI, calculated for the VAC section with $n = 1.06 \pm 0.02$, is $\varphi_b = (0.84 \pm 0.02)$ eV, whereas, if the drop of the forward bias across the series resistance was not taken into account, the same specimens demonstrated $\varphi_b = (0.73 \pm 0.02)$ eV at $n = 2.07 \pm 0.02$. For non-irradiated SDs fabricated on high-resistance substrates, the obtained value $\varphi_b = (0.80 \pm 0.02)$ eV at $n = 2.67 \pm 0.02$. With regard for the hole concentration in the initial crystal ($p = \frac{\sigma_p}{q\mu_p} = 4.2 \times 10^{14}$ m^{-3}), one can estimate the depth of the Fermi level in the semi-insulating semiconductor [13]: $\mu = \varphi_T \ln(N_v/p) = 0.51$ eV, where N_v is the density of energy states in the valence band ($N_v = 2(m_p kT/2\pi\hbar^2)^{3/2} = 2.7 \times 10^{23}$ m^{-3}), $m_p = 0.35 m_0$, m_0 is the electron mass, and $\hbar$ the Planck's constant.

The amplitude of band bending φ_0 can be determined either as the difference between the potential barrier height and the depth of the Fermi level μ in the energy gap ($\varphi_0 = \varphi_b - \mu$) or making use of the ($U = 0$)-values of the linear approximations of the dependences $1/C^2 = f(U)$ calculated from the results of VFC measurements. The value $\varphi_0^* = (2.01 \pm 0.02)$ eV obtained for various linear sections of the dependences $1/C^2 = f(U)$ presented in Fig. 2 is the same for irradiated and non-irradiated contacts and considerably exceeds the analogous value determined from VACs. In the case of structures on silicon substrates, this discrepancy can be explained by the formation of Al—n-Si contacts of the diffusion transition p^+—Si layer in the SCR [6]. Being normalized by the value of the dielectric permittivity of the material ε, the thickness of the transition region $d^* = d/\varepsilon$ is determined by the barrier capacity of the SD at zero bias. This model, being applied to the structures under investigation, gives rise to the thickness of the transition region $d^* \approx 1.1$ μm in non-irradiated contacts and $d^* \approx 1.7$ μm after LI if the material is high-resistance, and to $d^* \approx 0.1$ μm for structures fabricated on a low-resistance material. Such values of d^* are entirely in agreement with the theoretical estimations of the SRC thickness for semi-insulating p-CdTe with various levels of compensation [2]. Taking into account that chlorine is a donor impurity for p-CdTe, the probability of the formation of a n^+—p-CdTe transition at the MSC is rather high.

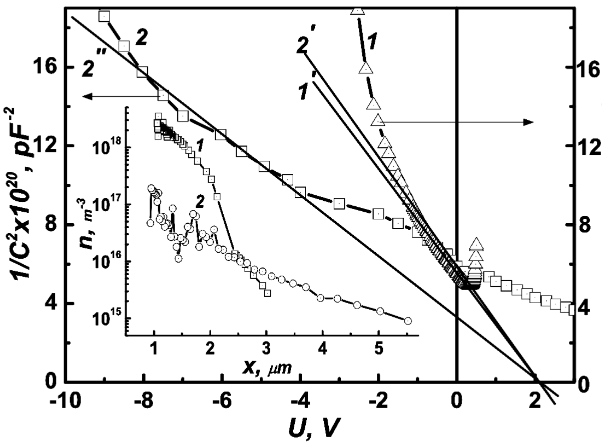

Fig. 2. Dependences $1/C^2 = f(U)$ and the distribution profiles of the electrically active impurity concentration in a Pt—p-CdTe:Cl Schottky diode on a low-resistance crystal before LI (*1*) and on a high-resistance crystal after LI (*2*). Curves $1'$, $2'$, and $2''$ are the approximations of the linear sections of the dependences $1/C^2 = f(U)$ in cases *1* and *2*

Another reason of the overestimated value of φ_0^* is the voltage drop of a high-frequency test signal f_{hf}, which is used for measurements of the SD barrier capacity C_b, across the series resistance of the diode base R_s. For example, at $f_{\mathrm{hf}} = 1$ MHz and $C_b = 30$ pF, the equivalent resistance of the barrier capacity X_c becomes comparable with the active resistance R_s: $X_c = (2\pi f_{\mathrm{hf}} C_b)^{-1} = 0.53 \times 10^4$ Ω. In the first approximation, this leads to the artificial enlargement of the voltage-axis scale by a factor of 2 while plotting the $1/C^2 = f(U)$ dependences. Using the approximations of the linear sections of these plots for graphic-analytical calculations of the band bending results in approximately the same overestimation of the φ_0^* value.

We calculated the distribution profiles of the electrically active impurity concentration in the near-contact layer of the semiconductor (see the inset in Fig. 2). By applying the technique of numerical differentiation of the experimentally measured VFCs, we obtained

$$n(x) = C^3 / \left(S^2 q \varepsilon \varepsilon_0 \left(dC/dU\right)\right), \quad (2)$$

where $\varepsilon = 10.6$ for CdTe, ε_0 is the electric constant, and the value of x-coordinate, $x = \varepsilon\varepsilon_0 S/C$, is determined by the barrier capacity at the point of differentiation.

After LI, a non-uniform distribution profile of the active impurity concentration is observed in the near-contact CdTe layer at depths from 1 to 2 μm. This indicates a redistribution of deep levels associated with impurity-induced structural defects in the transition MSC layer owing to LI. Here, the concentration of current carriers is 3—4 orders of magnitude higher than that in the SD base and reaches the value $n \sim 10^{17}$ m^{-3}. The distribution profile of active impurities is more monotonous as compared with that in a non-irradiated SD and, on the semi-logarithmic scale, is close to the linear law. One may state that the depth of the transition layer becomes 3—5 times as large after LI, and the resulting concentration of active impurities exponentially decreases with increase in the distance from the MSC.

The value of the activation energy E_a, which was determined from various linear sections of the semi-logarithmic VAC (Fig. 1, curve *2*) in supposition of the generation-recombination mechanism of current flowing in SDs fabricated on low-resistance crystals, is equal to $E_a = (0.58 \pm 0.02)$ eV. Within the limits of experimental errors, it agrees with the value $E_a = (0.60 \pm 0.02)$ eV obtained for the sections of experimental VACs for SDs on high-resistance crystals that were measured in the interval $0.075\ \mathrm{V} < U_{\mathrm{fwd}} \leq 0.2\ \mathrm{V}$ before LI and interpolated on the $\lg I = f(U - IR_s)$ scale. It should be noted that the indicated VAC sections are reflected adequately onto the corresponding sections of the dependence $\lg R_{\mathrm{diff}} = f(V)$ (see the inset in Fig. 1, plot *2*). It is of interest that the projections of points, where the sections of the linear approximation of the dependence $\lg R_{\mathrm{diff}} = f(V)$ intersect the line that corresponds to the resistance of the SD base, onto the bias-axis U_{fwd} are in a good agreement with the corresponding activation energy of the current flow mechanism that dominates in this voltage range. The values $E'_a = (0.58 \pm 0.02)$ eV and $E''_a = (0.72 \pm 0.02)$ eV that were deduced from individual sections measured before LI coincide with the values calculated from VACs. After LI, one can single out the most typical value $E'''_a = (0.43 \pm 0.02)$ eV in the dependence $\lg R_{\mathrm{diff}} = f(V)$.

The values of the activation energy determined for deep levels from VACs agree well with the data of other researchers. In particular, the authors of work [14] reported that they had identified two ground levels in p-CdTe, with $E'_t = 0.58$ eV and $E''_t = 0.44$ eV, using the DLTS method. The former is associated with the deformation potential caused by the "vacancy–interstitial Te atom" complex, the latter with the Cd vacancy. The reduction of the activation energy from $E'_a = (0.58 \pm 0.02)$ eV to $E'''_a = (0.43 \pm 0.02)$ eV after LI can be explained completely by the restructuring of the indicated structural defects owing to the emergence of thermoelastic stresses in the MSC during LI [15]. The same factor can stimulate the diffusion activation, accumulation of chlorine atoms in the SCR of a SD, and formation of vacancies. The latter occurs due to the displacements of cadmium atoms which possess a smaller ionic radius and a lower ionization energy in comparison with the relevant tellurium parameters [16].

The results exposed above give reasons to suggest that the band model of the SDs under investigation includes the region of inverse conductivity of the n^+-type, which causes the increase of the effective value of the potential barrier, especially after LI. In this case, the values of the contact parameters come closer to those of the perfect contacts ($n \to 1$), and the thermionic mechanism of charge transfer through the structure at forward biases $0.2\ \mathrm{V} < U \leq 0.4\ \mathrm{V}$ dominates. At lower biases ($0.075\ \mathrm{V} < U \leq 0.2\ \mathrm{V}$), the enhanced concentration of impurities and impurity-induced structural defects in the SCR of the MSC leads to the manifestation of other mechanisms of current flowing — the generation-recombination and, probably, tunnel and field ones. The growth of the total current in the indicated range of biases and the increase of n from 2.07 ± 0.02 to 2.76 ± 0.02 testify in favor of such mechanisms; the thickness of the transition layer can be a few microns at that. The series resistance of the diode base results in a significant deviation of the VAC from the linear dependence in the semi-logarithmic scale and its saturation at large forward biases. In the latter case, if the bands become straightened and the potential $\varphi_0 \to 0$, the field mechanism of current flowing, stimulated by the effect of modulation of the SD base region conductivity [2], can be observed.

4. Conclusions

As follows from the results of our experimental researches, the "tender" pulse laser irradiation of Pt–p-CdTe:Cl structures in optimal modes, when the interphase interaction at the MSC interface in the solid state becomes activated, can provide a substantial reduction of the generation-recombination component of the current through the barrier. It can be explained by the processes of restructuring of defect-impurity centers and, correspondingly, by the reduction of the concentration of deep levels in the SCR of the semiconductor. It has been experimentally shown that the main mechanism of current flowing in structures subjected to optimal LI is the thermionic overbarrier current, for which the measured height of the potential barrier in Pt–p-CdTe:Cl structures is $\varphi_b = (0.84 \pm 0.02)$ eV. The formation of a transition layer with inverse conductivity in the SCR of the contact can lead to an increase of the effective height of the potential barrier.

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ВПЛИВ ІМПУЛЬСНОГО ЛАЗЕРНОГО ВИПРОМІНЮВАННЯ НА ДЕТЕКТУЮЧІ ВЛАСТИВОСТІ КОНТАКТІВ Pt—p-CdTe:Cl З БАР'ЄРОМ ШОТТКІ

П.М. Горлей, О.І. Воробець, Г.І. Воробець, К.С. Ульяницький, В.В. Хомяк

Резюме

Вивчено фізичні механізми впливу імпульсного лазерного випромінювання мілісекундної тривалості підпорогової інтенсивності на формування перехідного шару і механізми протікання струму в діодах Шотткі (ДШ) Pt—p-CdTe:Cl. Розроблено методики і встановлено оптимальні режими лазерного опромінення структур Pt—p-CdTe:Cl, за яких можливе зменшення концентрації глибоких рівнів, пов'язаних із структурно-домішковими дефектами у напівпровіднику, і зменшення генераційно-рекомбінаційної складової струму в ДШ. Визначено величини потенціального бар'єра контактів Pt—p-CdTe:Cl $\varphi_b = (0,84{\pm}0,02)$ еВ та енергій активації глибоких рівнів $E'_a = (0,58{\pm}0,02)$ еВ, $E''_a = (0,72{\pm}0,02)$ еВ, $E'''_a = (0,43{\pm}0,02)$ еВ.