MECHANISMS OF MASS TRANSFER OF INDIUM IN CdTe UNDER NANOSECOND LASER IRRADIATION

**A. BAIDULLAEVA,[1] V.P. VELESHCHUK,[1] O.I. VLASENKO,[1]
V.A. GNATYUK,[1] B.K. DAULETMURATOV,[1] S.M. LEVYTS'KYI,[1] T. AOKI[2]**

[1]V. Lashkaryov Institute of Semiconductor Physics, Nat. Acad. Sci. of Ukraine
(41, Nauky Ave., Kyiv 03028, Ukraine; e-mail: `vvvit@ukr.net`*)*

[2]Research Institute of Electronics, Shizuoka University
(3-5-1 Johoku, Hamamatsu 432-8011, Japan)

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The mechanisms of pulsed laser solid-phase doping of CdTe with indium to produce diode structures for X-ray and gamma radiation detectors are considered. It is shown that the indium mass transfer in CdTe under nanosecond laser irradiation of the In–CdTe structure below the melting threshold of CdTe takes place by the barodiffusion mechanism due to a considerable stress gradient. We have calculated the mass transfer coefficients of indium and estimated the mean drift velocity of indium atoms in CdTe under irradiation of the In–CdTe structure with the 30-nm-thick In film by a nanosecond excimer laser pulse at $E = 100$ mJ/cm^2 being the optimal energy density for the doping.

1. Introduction

The phenomenon of high mobility of atoms in crystals under pulsed laser irradiation (PLI) is currently of high applied importance for the solid-phase doping of CdTe by means of the irradiation of metal-CdTe structures by laser pulses. It is due to the effectiveness, processability, reproducibility, and simplicity of choosing the parameters when producing X-ray and gamma sensitive detectors with low noise level and high spectrometric characteristics on the basis of diodes with an abrupt p-n junction at a low depth [1, 2].

At the same time, the mechanisms of mass transfer in "metal film–semiconductor" structures under PLI are now studied insufficiently to predict and to purposefully change the electric and photoelectric characteristics of semiconductor structures with a p–n junction and ohmic and rectifying contacts [1–8], especially CdTe-based ones used for ionizing radiation detectors [1, 2]. The clarification and the analysis of mass transfer mechanisms are necessary to determine the optimal modes of nanosecond laser solid-phase doping of CdTe and similar "metal film–semiconductor" structures with indium.

The complexity of the mass transfer mechanisms under nanosecond PLI is caused by the nonstationarity, nonequilibrium, physical and geometrical nonlinearities, and high speed and synchronism of various physical processes; among them, there are a variation of the aggregate state of a solid body, generation of elastic and shock waves, considerable temperature and stress gradients, defect formation, diffusion, and so on.

The aim of this work was to establish and to analyze the dominant mechanisms of indium mass transfer in CdTe under nanosecond laser irradiation of In–CdTe structures.

2. Experiment

We analyze the concentration profile of indium atoms in the (111) CdTe monocrystal after the single irradiation of the In–CdTe structure from the side of the 30-nm-thick indium film by an excimer laser pulse with $\lambda = 0.248$ μm, the duration $\tau_p = 20$ ns, and the energy density $E = 100$ mJ/cm^2 (Fig. 1). This profile was obtained in our earlier work [1] with the help of Auger spectroscopy after the layer-by-layer etching by an argon ion beam. Such profiles of the impurity distribution in CdTe under PLI were also obtained in some other studies [5, 6].

One can see from curve 1 in Fig. 1 that the penetration depth of indium atoms in the crystal reaches 60 nm from the CdTe surface. In this case, one observes a characteristic peak at the depth $x = 6$ nm, which is explained by the presence of a directed flow of atoms into the crystal along the x axis with the mean drift velocity $\langle \upsilon_x \rangle$ [8–12]. The appearance of the maximum is of threshold character – it is formed at $\langle \upsilon_x \rangle^2 t > 2D$ (1) [10–12], where D is the mass transfer coefficient, and t is the total time of laser radiation, partial evaporation of the film, and relaxation of the temperature gradient and thermoelastic stresses in the diffusion zone. The time $t = 100$ ns is determined from the temperature profile

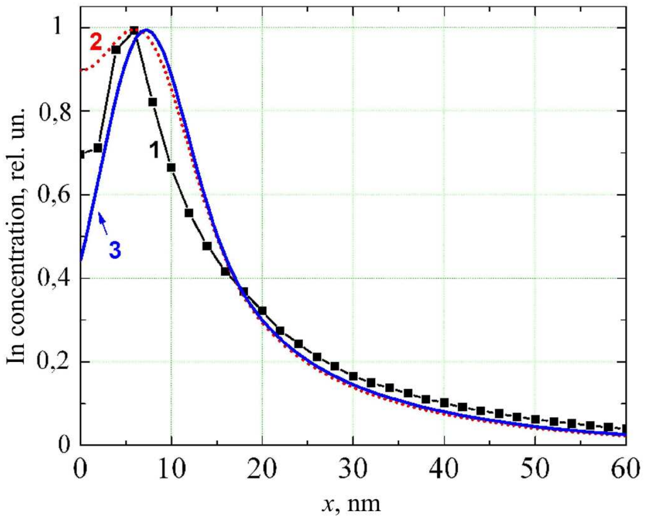

Fig. 1. Concentration profile of indium atoms in a CdTe monocrystal: experiment (*1*) and the approximation by 4 exponents according to formulas (1) (curve *2*) and (2) (curve *3*)

of In–CdTe under irradiation and represents the time of effective mass transfer or the time of action of forces caused by the temperature and stress gradients. After 100 ns, the mass transfer processes are practically frozen and have a relaxation character.

Taking into account that, in our case, the PLI results in the evaporation of a thin indium film, one can use the model of diffusion from an infinitely thin layer. Then the concentration profile with regard for the kinetics of penetration of indium atoms into CdTe at $C(x,0) = C_0\delta(x)$ can be described by the expression taken from work [12]

$$C(x,t) = \frac{C_0}{2\sqrt{\pi Dt}}\left[\exp\left(-\frac{(x-\langle\upsilon_x\rangle\, t)^2}{4Dt}\right) + \right.$$

$$\left. + \exp\left(-\frac{(x+\langle\upsilon_x\rangle t)^2}{4Dt}\right)\right] \quad (1)$$

or [10]:

$$C(x,t) = \frac{C_0}{2\sqrt{\pi Dt}}\exp\left(-\frac{(x-\langle\upsilon_x\rangle\, t)^2}{4Dt}\right) -$$

$$-\frac{C_0\,\langle\upsilon_x\rangle}{4D}\exp\left(\frac{\langle\upsilon_x\rangle\, x}{D}\right)\operatorname{erfc}\left(\frac{x+\langle\upsilon_x\rangle\, t}{2\sqrt{Dt}}\right), \quad (2)$$

where C_0 is the initial concentration of indium atoms on the surface ($x = 0$), and $\delta(x)$ is the delta function.

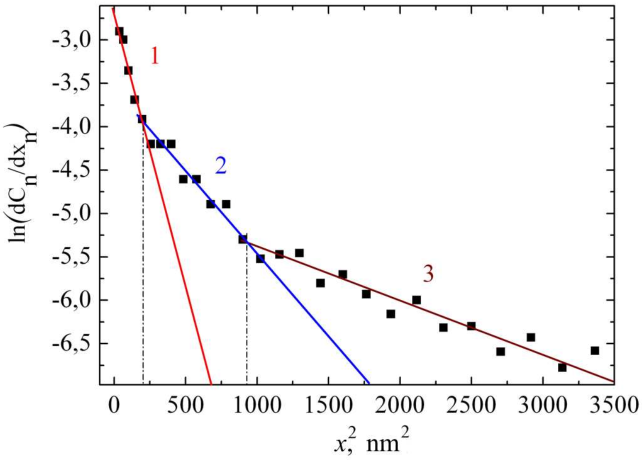

Fig. 2. Linearized representation of the concentration profile of indium atoms in CdTe based on Fig. 1

In this case, the mass transfer process under PLI can be described using the Manning formalism about the existence of a driving force producing a directed flow of atoms with the velocity $\langle\upsilon_x\rangle$ and its significant influence on mass transfer [9–11]. The mass transfer coefficient D was determined from the expression $D = (4t\,\mathrm{tg}\alpha)^{-1}$, where α is the slope angle of the curve $\ln(\Delta C_n/\Delta x_n) = f(x_n^2)$ reconstructed from the dependence of the concentration profiles of In atoms in CdTe (Fig. 1, curve *1*) by means of the graphical differentiation according to a procedure described in [12–14].

Figure 2 shows the distribution of indium atoms in CdTe in the coordinates $\ln(\Delta C_n/\Delta x_n) - x^2$ at $x > 6$ nm, which is the linearization of the curve in Fig. 1, since the indium concentration decreases approximately exponentially according to expressions (1) and (2). This distribution includes three characteristic linear regions, where the mass transfer coefficients of indium in CdTe during PLI are equal to (*1*) – $D_1 = 3.9\times10^{-6}$ cm^2/s, (*2*) – $D_2 = 1.46\times10^{-5}$ cm^2/s, and (*3*) – $D_3 = 5.2\times10^{-5}$ cm^2/s.

It is evident from Fig. 2 that the mass transfer coefficient increases with depth; in the near-surface layer (up to 14 nm), it is lower than that in the crystal bulk. The same regions with different D or kinks in the distribution of diffusing elements (radioactive isotopes of metals) were observed in various metals (Fe, Mo, Nb, Ti, and Al) after their deformation by a pulsed mechanical loading resulting from a shock with a relative deformation rate ranging from 1 to 100 s^{-1} at elevated temperatures [16], as well as in [10, 15] under conditions of external pulsed influences.

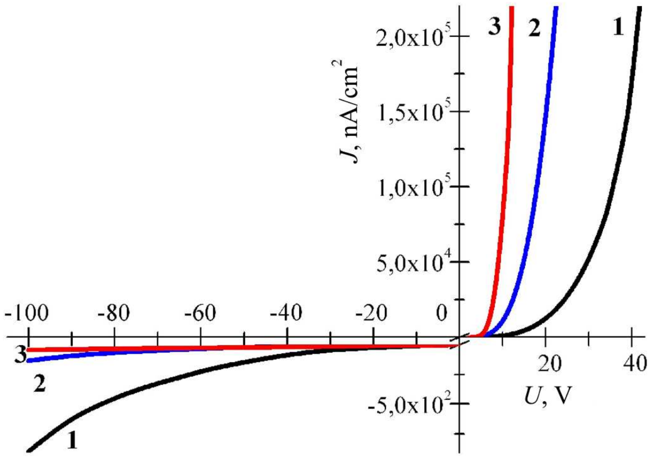

Fig. 3. Current-voltage characteristics of the In–CdTe–Au structure before (curve *1*) and after (curves *2, 3*) irradiation by nanosecond pulses of a KrF excimer laser in the argon atmosphere at $E = 86$ mJ/cm^2 (1) and $E = 108$ mJ/cm^2 (2). $T = 300$ K

The linear regions in Fig. 2 testify to the bulk character of the mass transfer process in contrast to the grain and subgrain boundary diffusion. In our case, the CdTe single crystal is grown by the low-temperature synthesis technology, and the polycrystalline structure was practically absent. Moreover, the dislocation density did not exceed $\rho_{\text{disl}} \approx 10^4$ cm^{-2}.

Since the linearized concentration profile includes three kinks corresponding to three exponents, the whole experimental profile can be approximated by four exponents. The fourth exponent corresponds to the diffusion in the peak region (in the interval between 0 and 10 nm) with another diffusion coefficient D_0 less than D_1 by the quantity $n = D_3/D_2 \ldots D_2/D_1$. Curves *2* and *3* in Fig. 1 correspond to the approximations by four exponents according to formulas (1) and (2), respectively, using the following parameters: $D_0 = 1.1 \times 10^{-6}$ cm^2/s, $D_1 = 3.9 \times 10^{-6}$ cm^2/s, $D_2 = 1.46 \times 10^{-5}$ cm^2/s, $D_3 = 5.2 \times 10^{-5}$ cm^2/s, and $\langle \upsilon_x \rangle = 6$ cm/s. The calculation of the velocity will be presented in what follows. This approximation provides a good description of the experimental profile of indium. It is worth noting that, in order to consider the effect of a variation of dimensions of the sample in the process of deformation, the correction (multiplier) $a = 2\varepsilon_{\max}/(e^{2\varepsilon_{\max}} - 1)$ was introduced for the diffusion coefficient D, where $\varepsilon_{\max}$ stands for the deformation [10, 14, 15]. However, in our case, a is at least 0.9, whereas D_0, D_1–D_3 differ by a factor of 3.7.

The presence of indium mass transfer in CdTe under PLI by an excimer [1] or ruby [7] laser (nanosecond laser solid-phase doping) is also indicated by changes of the current-voltage characteristics (CVC). Figure 3 presents the CVCs of the In–CdTe–Au structure in the initial state (curve *1*) and after a single irradiation (curves *2,3*) from the side of the 400-nm indium film by an excimer laser in the argon atmosphere at a pressure of 3 atm. The form of the CVC after the irradiation testifies to the intensification of the rectifying properties of the structure due to the indium doping of the near-surface CdTe layer and the formation of a p–n junction in the same way as in [1]. The leakage current density at a reverse bias of –100 V fell from 900 nA/cm^2 (curve *1*) to 135 nA/cm^2 (curve *2*) and 45 nA/cm^2 (curve *3*). Respectively, the noise level of such a detector structure will decrease.

3. Peculiarities of Indium Mass Transfer in CdTe. Barodiffusion and Thermal Diffusion

The indium diffusion in CdTe due to the pulsed laser irradiation takes place under the conditions of considerable gradients of the temperature and thermoelastic (and plastic) stresses caused by the strongly depth-nonuniform heating.

According to our calculations, the pulsed laser irradiation of a structure at the energy density $E = 50 - 400$ mJ/cm^2 and the optical reflection coefficient of indium $R = 0.8$ results in the following rates of increase and the depth gradients of the temperature and the pressure: $dT/dt = 6 \times 10^9 - 5 \times 10^{10}$ deg/s, $dT/dx = 10^8 - 10^9$ deg/m, $dP/dt = 4 \times 10^{15} \ldots 10^{16}$ Pa/s, and $dP/dx = 3 \times 10^{13} - 3.6 \times 10^{14}$ Pa/m.

The longitudinal pressure gradient in the solid phase under PLI $\frac{dP}{dx} = \alpha_T(T) E \frac{dT}{dx}$ was calculated with regard for both the temperature profiles for deriving dT/dx and the pressure P on the surface. Here, E is the Young modulus, and $\alpha_T(T)$ is the linear thermal expansion coefficient. The mechanical force [8, 17]

$$F_P = \frac{4}{3} \frac{1 - \nu^2}{(1 - 2\nu)^2} G(\Omega_i - \Omega_0) \nabla(\alpha_T T) \qquad (3)$$

results in the diffusion of indium atoms caused by the difference of the covalent radii (dilatation volumes) of the In impurity and Cd or Te or in the barodiffusion. The thermal force [8, 17]

$$F_T = -\frac{1}{3} \Omega_0 C \langle \sigma_0/\sigma_i \rangle \nabla T \qquad (4)$$

gives rise to the thermal diffusion due to the phonon capture of impurity atoms, at which they are transferred from hot places to cold ones. Here, ν is the Poisson's ratio, G is the shear modulus, Ω_0 and Ω_i stand for the elementary volumes of atoms of the basic substance and the impurity, respectively, C is the heat capacity, and $\langle\sigma_0/\sigma_i\rangle$ is the averaged ratio of the cross sections of phonon scattering by atoms of the basic substance and the impurity, respectively. The forces caused by the gradients of elastic stresses F_P and the temperature F_T result in the transfer of indium atoms with the drift velocity [8, 17]

$$\upsilon = D(F_P + F_T)/kT. \tag{5}$$

The covalent radii of indium, cadmium, and tellurium atoms are equal to 1.44 Å, 1.48 Å, and 1.32 Å, respectively. Due to the difference of the dilatation volumes, indium will diffuse into CdTe substituting Te ($\Omega_0 < \Omega_i$) due to the barodiffusion mechanism. In addition, In atoms in Cd vacancies will be captured by an elastic wave, since p-conduction was established to be inverted into n-type one due to the occupation of cadmium vacancies by In atoms [1]. The substitution of Cd atoms by indium is also possible ($\Omega_0 > \Omega_i$), but this flow will be directed to the CdTe surface. Thus, in the general case, there can exist two oppositely directed flows of In atoms, which is taken into account in expression (1) (two terms).

In our case, the absolute value of the force $|F_P|$ is larger than $|F_T|$ by a factor of $(1.5\text{–}7.1)\times10^3$. That is why the dominant mass transfer mechanism is the atom transfer under the action of the mechanical force F_P or the barodiffusion mechanism caused by a significant gradient dP/dx. The value of $\langle\sigma_0/\sigma_i\rangle$ is of the order of 1 [18, 19]. Since the force F_P is higher than F_T, the flow direction depends on the sign of the difference $\Omega_i - \Omega_0$. We have $\upsilon \sim \nabla(\alpha_T T)$; therefore, the velocity of indium atoms reaches a maximum in the region of the largest values of $\nabla(\alpha_T T)$. The calculation of the velocity of indium atoms in the field of thermoelastic stresses using formula (5) with regard for the experimentally determined D yields the range $\upsilon \approx 0.2\text{–}2.6$ cm/s (tellurium atom diffusion at $D = 3.9\times10^{-6}$ cm^2/s–5.2×10^{-5} cm^2/s).

In the case of a high-energy action realized under the nanosecond irradiation, the crystal is "pumped" with the energy accumulated in the form of excited states of interstitial atoms (IA) and vacancies. Subsequently, this energy is released in the form of flows of IAs, vacancies, and atoms in the field of thermoelastic stresses. Under PLI, the diffusion is predominantly interstitial [10, 15].

If the energy of a diffusing atom exceeds the height of potential barriers of lattice atoms or the activation energy of motion ΔE, then IAs will move in the elastic wave field without activation and there takes place their "capture" [20]. If the value of ΔE exceeds the thermal vibration energy (kT), then the mass transfer mechanism is of nondiffusion nature [15]. However, in this case, the pressure gradient dP/dx in an elastic pulse must reach 5×10^{18} Pa/m [20, 21]. That is why the above-calculated stress gradients are insufficient for the completely activationless motion of In atoms, particularly IAs. Nevertheless, they are large enough for the fast thermally activated motion of In atoms in the direction of the force elastic field with the drift velocity $\upsilon = DF_P/kT$. Thus, indium atoms and IAs move in CdTe by means of thermal fluctuation jumps under the action of a driving force F_P.

The mean velocity of a directed motion of indium atoms in CdTe can be also estimated from the experimental profile (Fig. 1). We consider the synchronism of the processes of evaporation of the film surface and mass transfer – the approximate transport length of indium atoms is assumed to lie between 6 and 15 nm + 6 nm, which corresponds to the sum of the half-thickness of the indium film and the distance to the peak in Fig.1, where the concentration of In atoms reaches a maximum and is caused by their transport with the velocity $\langle\upsilon_x\rangle$. Then $\langle\upsilon_x\rangle$ = (6–21 nm)/100 ns = 6–21 cm/s, and criterion (1) is satisfied with regard for the mass transfer coefficient of indium in CdTe in the peak region of Fig. 1. This velocity of indium atoms in CdTe is of the order of the velocity of Zn ions in the p–n-junction of GaAsP structures (14 cm/s) at their shift caused by the gradient of thermoelastic stresses under PLI [17]. It also coincides with the mean velocity of atoms $\langle\upsilon_x\rangle \approx 13$ cm/s in the near-surface layer of metals under their nanosecond PLI [12]. The maximum velocity of impurity Cu atoms in GaAs under PLI obtained theoretically in [8] reaches $\upsilon = 180$ cm/s. It was also shown that the maximum in the velocity distribution of impurity atoms corresponds to the peak value of thermoelastic stresses and the temperature gradient.

The velocity of substance particles (velocity of a facet under compression) in the simplest problem of an impact caused by a constant compressive force suddenly applied to a body with regard for its continuous deformation and inertia properties can be also estimated by the formula $\upsilon = \sigma/\sqrt{\rho E}$ [22]. Here, ρ is the density, σ is the normal stress in the cross section, and $\upsilon = 24$ cm/s at $\sigma = 2.15$ MPa (ultimate strength of In under compression).

As was noted, we registered an increase of the mass transfer coefficient of In atoms in CdTe with depth under PLI. The same growth of D with depth was observed in the case of a linearized distribution of radioactive isotopes of metals in various metals after their deformation by a pulsed mechanical loading [16]. That work, as well as works [10, 11, 15], reports on kinks registered in the linearized concentration distributions due to the difference of atom mobilities at different depths. Moreover, the deformation distribution in the diffusion zone was also nonuniform. In addition, calculations performed in [8] demonstrated an increase of the velocity of diffusing atoms under PLI with depth (and with time, in the process of mass transfer). This fact testifies to the dependence of the mass transfer coefficient of diffusing atoms on the distance from the surface in the case of a pulsed influence.

The increase of the diffusion coefficient with the distance can be explained as follows. Since atoms start moving practically simultaneously (synchronously) with the generation of a compression wave, the diffusing atoms and the deformation pulse first propagate together (atoms in a compressed lattice, D_0). After that, the compression wave gradually appears ahead due to the larger propagation velocity (D_1), and atoms go on moving in a less deformed lattice (D_2) and then in a still less deformed one (D_3). Moreover, the trailing edge of a deformation wave represents a stretching deformation, because, according to [8], the PLI of a semiconductor results in the change of the sign of elastic stresses in the distribution of thermoelastic stresses in the near-surface layer, which corresponds to the presence of a stretching region near the compression one. That is why, atoms moving in another (deeper) region of the crystal will appear in a less compressed lattice, and their diffusion coefficient will rise due to a change of the multiplier D_a in the diffusion coefficient and the quantity $E_{\text{act}} - D = D_a \exp(-E_{\text{act}}/kT)$, where $D_a = a^2/\tau_0$, a is the lattice constant, and $\tau_0 \sim 10^{-13}$ s is the time of the order of the vibration period of atoms in the crystal lattice (corresponding to the acoustic spectrum frequency). Thus, atoms actually move in the lattice with a varying deformation. Respectively, their diffusion coefficient changes from one region to another. In other words, this fact can explain the evolution of the maximum gradients of the temperature and stresses, which results in a partial capture and a redistribution of indium atoms.

The above-calculated mass transfer coefficient of In in CdTe significantly exceeds the coefficients of concentration diffusion of impurities at high T in semiconductors (under the common annealing conditions and the diffusion technique of introducing an admixture) and is of the order of the self-diffusion coefficient in the majority of liquid metals $\sim 10^{-4} - 10^{-6}$ cm^2/s and the diffusion coefficient of Ag in CdTe under PLI – $(3.97\text{–}7.2)\times10^{-6}$ cm^2/s at $E = 20$ and 30 J/cm^2, $\tau_p = 3$ ms obtained in [6]. That work also reports on the oscillating distribution of In impurity in CdSb down to 75 μm at $E = 14$ J/cm^2. In [13], the mass transfer coefficient in iron under PLI at $E_S = 240$ mJ $\tau_p = 30$ ms, and $n = 10$ pulses amounts to 1.6×10^{-2} cm^2/s. At $I = 10^7$ W/cm^2 in iron, $D = 3\times10^{-5}$ cm^2/s [12]. As was shown in [10], in nickel under PLI, $D = (1.2\text{–}11.5)\times10^{-5}$ cm^2/s; while, at $E_S = 5$ J and $\tau_p = 50$ ns ($n = 5\text{–}20$), $D\,^{55.59}$Fe in Fe is equal to $(0.33\text{–}0.61)\times10^{-2}$ cm^2/s, $D\,^{95}$Nb in Fe amounts to $(1.12\text{–}3.12)\times10^{-2}$ cm^2/s. The coefficient $D\,^{137}$Cs in Fe is equal to $(2.4\text{–}6.7)\times10^{-5}$ cm^2/s at $E_S = 5$ J and $\tau_p = 50$ ns [23]. These data are commensurable with our values of D. In [24, 25], it was found out that the coefficient D of copper atoms in nickel at $I = 10^9\text{–}10^{10}$ W/cm^2 and $\tau_p = 30$ ns amounts to 100 cm^2/s.

As was shown in our earlier work [7], the formation and the propagation of a shock wave and the mechanism of concentration diffusion alone are not direct or dominant mechanisms of indium mass transfer in CdTe under nanosecond PLI. We calculated the temperature of the heated surface of the In–CdTe structure and demonstrated that the diffusion processes take place in the solid phase of CdTe. At $E = 100$ mJ/cm^2 (irradiation mode optimal for doping), the maximum temperature of the indium film with the thickness $h = 400$ nm amounts to 220 °C ($R = 0.8$) and 440 °C ($R = 0.6$). At $h = 30$ nm, $T = 510$ °C ($R = 0.8$) and 1020 °C ($R = 0.6$), which exceeds the melting temperature of indium (157 °C), though it is less than the melting temperature of CdTe (1067 °C).

The shock deformation and, respectively, the generation of a compression pulse under the nanosecond laser irradiation of In–CdTe occur due to the following processes:

1. Very fast (20-nanosecond) heating (heat shock) and, respectively, deformation with the deformation rate $\dot{\varepsilon}_{zz} = \frac{\varepsilon_{zz}}{\tau_p} = \frac{1+\nu}{1-\nu}\frac{\alpha_T \Delta T}{\tau_p}$ [10, 26]. Under PLI in the temperature range 500–1000 °C, the deformation rate for indium ($\nu = 0.46$) $\dot{\varepsilon}_{zz} \approx (2\text{–}4)\times10^6$ s^{-1}, while for CdTe, $\dot{\varepsilon}_{zz} \approx (2.5\text{–}5.6)\times10^5$ s^{-1}.
2. Fast (shock) "solid body–liquid" phase transition. In the general case, $\dot{\varepsilon} = \frac{\Delta h/h_0}{\tau_p} = \frac{{}^{1/3}\sqrt{\Delta V/V_0}}{\tau_p}$ [10, 15, 16], where Δh is a change in the linear dimension, ΔV is the volume increment due to the melting, and h_0 is the initial size of a near-surface layer of the volume V_0 at the heat diffusion depth. For In, $\Delta V/V_0 = 2.5$ %, which corresponds to 1.36 % for Δh. Then $\dot{\varepsilon} = 0.0136/20$ ns $= 6.8\times10^5$ s^{-1} and higher, as the indium film is heated to the temperature exceeding the melting one.

As was shown in [27], the process of fast increase of the sample volume due to the explosive $\gamma \rightarrow \alpha$-transformation of Fe–Ni alloy at the nitrogen and helium temperatures (second-order phase transition) results in the mass transfer to a larger depth (up to 30 μm) during the phase transition. Moreover, experiments revealed a considerable growth of the penetration depth of radioactive isotopes under the synchronous action of the deformation and the second-order phase transition due to fast cooling.

3. Fast evaporation from the surface and, respectively, generation of a recoil pressure from nonequilibrium vapors.

4. Optical breakdown in vapors and formation of a plasma (by the trailing edge of a laser pulse). The absorbed radiation, ionization, and breakdown result in the formation and the fast expansion of a plasma. The abrupt vapor heating and the resulting expansion of a cloud of a hot plasma above the sample surface at the light detonation due to the pulsed laser plasma formation also excite a pulse of the significant recoil pressure.

The integral action of these four mechanisms of pressure generation result in the barodiffusion due to the total pressure $P = P_T + P_{\text{sol.-liq}} + P_{\text{pairs}} + P_{\text{det}}$. The smallness of the theoretically calculated velocity of In atoms under the action of the force F_P (3) as compared to the experimentally obtained one is probably explained by that only the first term P_T was taken into account.

Summing up all the above-written, the process of penetration of indium atoms into CdTe can be qualitatively explained in the following way. Due to the fast (actually shock, $\dot{\varepsilon} > 10^5$ s^{-1}) effect of the nanosecond PLI of In–CdTe, the rate of increase of the temperature and the pressure, as well as the recoil pressure, at a deformation, the phase transition in indium, and the generation of vapors and a plasma with shock rates of increase are so high that there appears a compression pulse with a significant stress gradient. The summary pulse propagates inward and stimulates the intense barodiffusion of In in CdTe. Moreover, the experiments demonstrate an increase of the coefficient D with the distance, which agrees with the fact of a growth of the atom mobility with the depth [10, 16, 21], while the large values of D result from the specific character of mass transfer under conditions of a pulsed dynamic influence, where the mass transfer coefficient of atoms strongly grows in the direction of propagation of the deformation pulse front.

Indium atoms (mainly interstitial ones, due to tens times smaller E_{act} of migration) are captured by the front and the gradient P of a deformation pulse and are transferred at the distance determined by the PLI duration and the relaxation time of thermal stresses. The thermal plasticity processes result in the intense structural relaxation in the indium film, because the plastic limit of CdTe is larger than that of In approximately by a factor of 25.

It is worth noting that these results can be applied to the majority of “film–semi-infinite solid body” structures, especially “metal film–semiconductor” ones for the pulsed solid-phase doping and the formation of rectifying and ohmic contacts when producing devices of photo- and optoelectronics, and so on.

4. Conclusions

It is established that the dominant mass transfer mechanism at the nanosecond laser solid-phase doping of CdTe with indium is the barodiffusion. A relatively deep and fast penetration of indium atoms into CdTe in the case of nanosecond laser irradiation of the In–CdTe structures at laser pulse energies below the melting threshold of CdTe is caused by the significant elastic stress gradients arising due to the fast processes of heating, melting, vapor and plasma formation with “shock” rates. That is why, to create detectors with an abrupt p–n junction at a small depth with the help of the solid-phase pulsed laser doping of CdTe, it is appropriate to provide large and sharp pressure gradients, rather than heating. For example, it can be realized by irradiating the structure in a transparent liquid or material (fixed external facet).

We determined the mass transfer coefficients of indium in CdTe in various regions of the In–CdTe structure with the 30-nm-thick indium film subjected to the nanosecond irradiation by an excimer laser from the metal side at $E = 100$ mJ/cm^2: $D_0 = 1.1\times10^{-6}$ cm^2/s, $D_1 = 3.9\times10^{-6}$ cm^2/s, $D_2 = 1.46\times10^{-5}$ cm^2/s, and $D_3 = 5.2\times10^{-5}$ cm^2/s. It was established that the mass transfer coefficient of indium atoms in CdTe depends on the distance from the CdTe surface and increases due to the time evolution of a nonuniform deformation of the crystal lattice in the process of indium diffusion.

It is established that the mean drift velocity of In atoms in CdTe at the nanosecond laser irradiation of the In–CdTe structure with a 30-nm-thick In film at $E = 100$ mJ/cm^2 amounts to several to tens of centimeters per second, according to different estimates.

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МЕХАНІЗМИ МАСОПЕРЕНОСУ ІНДІЮ В CdTe ПРИ ДІЇ НАНОСЕКУНДНИХ ЛАЗЕРНИХ ІМПУЛЬСІВ

А. Байдулаєва, В.П. Велещук, О.І. Власенко, В.А. Гнатюк, Б.К. Даулетмуратов, С.М. Левицький, Т. Аокі

Резюме

Розглянуто механізми імпульсного лазерного твердофазного легування CdTe індієм при створенні діодних структур для детекторів рентгенівського і гамма-випромінювання. Показано, що масоперенос індію в CdTe при наносекундному лазерному опроміненні структури In–CdTe до порога плавлення CdTe відбувається за механізмом бародифузії – внаслідок значного градієнта напружень. Розраховано коефіцієнти масопереносу індію та оцінено середню дрейфову швидкість переміщення атомів In в CdTe під час опромінення наносекундним імпульсом ексимерного лазера структури In–CdTe з товщиною плівки In 30 нм при оптимальному для легування значенні густини енергії $E = 100$ мДж/см^2.