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Accumulation of Radiation-Induced Defects in CdTe Implanted by Kr^+ Ions — in-situ Investigations

Zmiany koncentracji defektów w CdTe implantowanym jonami Kr^+ — badania *in-situ*

1. INTRODUCTION

It is well known, that the total amorphization of CdTe, obtained in the process of implantation, occurs only much below than the room temperature [1, 2]. This clearly shows that radiation-induced fundamental defects, accumulation of which should lead to amorphization, have sufficiently low annealing temperatures. For this reason, application of a traditional research procedure, such as implantation in low temperatures and consecutive measurements of properties of the material in the room temperature, can result in considerable inaccuracy since in the samples put into the room temperature uncontrolled annealing of a part of defects may appear. The inaccuracy can be reduced when the implantation and measurements are carried out at the same time and constant temperature (the *in situ* method).

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2. EXPERIMENTAL PROCEDURE

In order to investigate the kinetics of defect accumulation the *in situ* method of measurements with the He–Ne laser light reflection has been used. Accumulation of radiation-induced defects leads to changes of optical parameters of studied semiconductors or dielectrics and, subsequently, to a change of the reflection coefficient [3, 4].

In these investigations an ion implanter UNIMAS-79 in the Institute of Physics UMCS [5] has been used. Schematic diagram of the experimental equipment is shown in Figure 1. Beam of light from He–Ne laser (1)

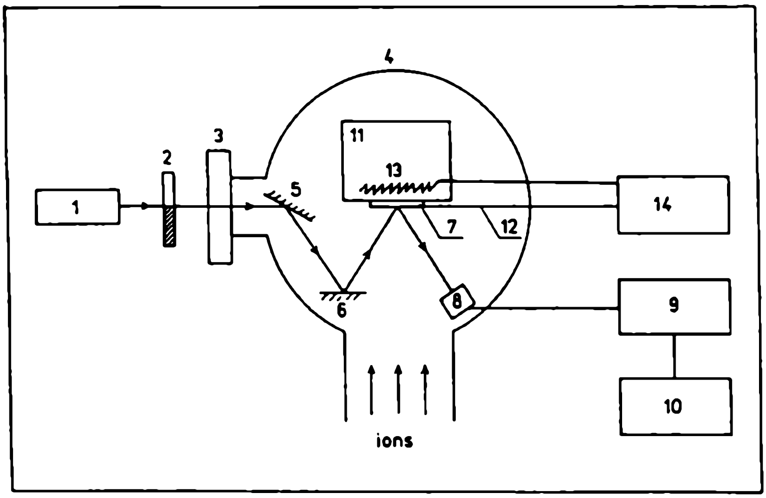

Fig. 1. Schematic diagram of the experimental equipment for *in-situ* measurements of reflected light intensity
Schemat stanowiska do *in-situ* pomiarów natężenia światła, odbitego od implantowanej próbki

goes through a chopper (2), then through a transparent window (3) into a chamber of implanter (4). A system of mirrors (5, 6) directs it to the implanted surface of the Cd–Te sample (7) at the angle of 5°. The reflected light travels to a detector (*e*). The signal which is proportional to the intensity of reflected light goes from the detector to a selective voltmeter (9) and is registered by a recorder (10). A 0sample has been fixed on a cold finger of cryostat (11). Temperature was measured with a termoelement (12). The heater (13) and termoregulator (14) have been used to hold temperature constant in the range of 77–500 K with accuracy ± 2K. Mechanically polished crystalline samples of CdTe have been etched in a solution of bromium in ethanol and then rinsed in ethanol. Energy of Kr^+ used in the experiment was 90 keV and density of ionic current was 1 $\mu A/cm^2$.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The reflected light intensity change ΔI versus dose of implanted Kr^+ ions D is shown in Figure 2 for selected temperatures. The analysis of the curves $\Delta I = f(D)$ allows for determining the dose of ions needed to achieve the saturation (D_a) and related to it change of the light intensity ΔI_n (Figure 2).

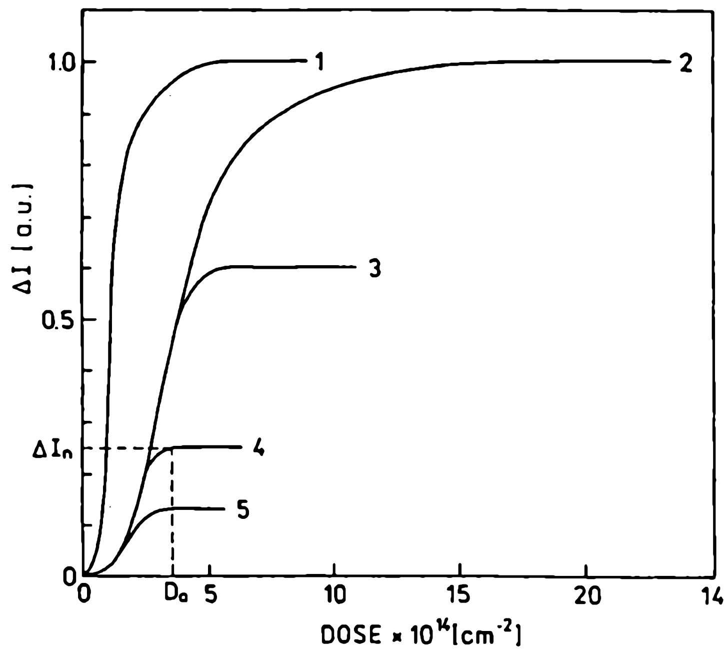

Fig. 2. Relationships of changes (ΔI) of light reflected by implanting sample CdTe versus dose of Kr^+ ions for various temperatures of implantation. 1 — 100 K, 2 — 128 K, 3 — 216 K, 4 — 250 K, 5 — 288 K; energy of ions is $E = 90$ keV, ions current $j = 1$ μ A/cm^2)
Przebiegi natężenia światła (ΔI), odbitego od implantowanej próbki CdTe w zależności od dawki jonów Kr^+ dla różnych temperatur implantacji. 1 — 100 K, 2 — 128 K, 3 — 216 K, 4 — 250 K, 5 — 288 K; energia jonów $E = 90$ keV, gęstość prądu jonowego $j = 1$ μ A/cm^2)

Near the critical temperature 120 K, when the maximal value of D_a is achieved, the dependence of ΔI versus dose reveals the nontypical behaviour. Experimental curve exhibits some apparent oscillations (Figure 3).

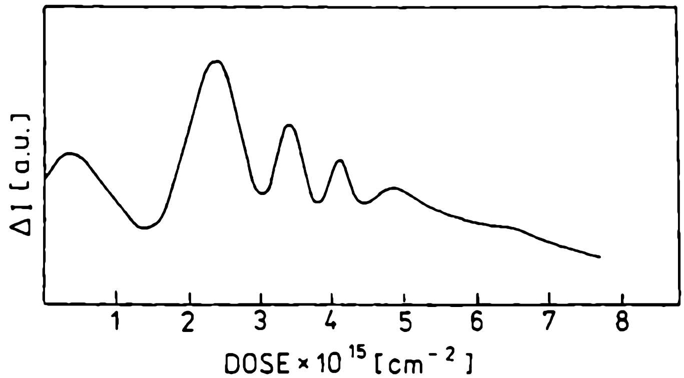

Fig. 3. Relationship of changes (ΔI) of light reflected by sample Cd Te versus dose of Kr^+ ions for implantation carried out at temperature 120 K; energy of ions is $E = 90$ keV, ions current $j = 1$ μ A/cm^2
Przebieg natężenia światła odbitego (ΔI) od implantowanej próbki CdTe w zależności od dawki jonów Kr^+ dla temperatury implantacji 120 K; energia jonów $E = 90$ keV, gęstość prądu jonowego $j = 1$ μ A/cm^2

Figure 4 shows dependences of dose D_a and the reflected light intensity change ΔI_n versus temperature of implanted sample. In low temperature range (100–120 K) steep rise of dose D_a is observed. Further rise of temperature causes a decrease of this dose as well as a decrease of the light intensity change ΔI_n related to the state of saturation. At last, when $T = 300$ K, implantation of Kr^+ ions up to the dose 2×10^{16} cm^{-2} does not affect the value of change of light intensity reflected from Cd Te sample and D_a cannot be determined.

In earlier studies, carried out with the use of the same method but for implanted silicon samples, it was observed that during implantation for some dose of ions the optical parameters as well as the reflection coefficient became stable [6]. The dose D_a, corresponding to saturation in the relationship $\Delta I(D)$, has been recognized as a dose of full amorphization of the sample. The relation $D_a(T)$ was monotonically rising with temperature.

Therefore, from the point of saturation of the reflection coefficient function versus a dose of implanted ions, the achievement of implanted state could be estimated.

Assuming that this correlation between the point of achieving the saturation and dose of amorphization for CdTe samples is maintained, the behaviour of amorphization dose $D_a(T)$ versus temperature is abnormal.

The rise of amorphization dose with temperature, which is observed for most semiconductors, is connected with an increasing amount of defects annealed during implantation. For this reason, to accumulate critical den-

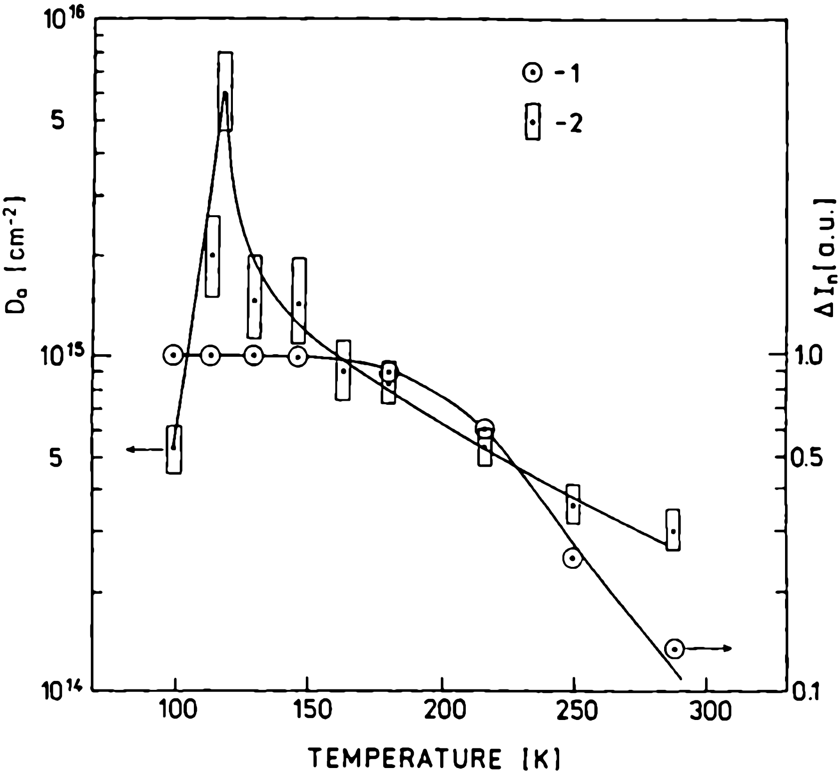

Fig. 4. Temperature dependence of reflected light change (ΔI for dose for which saturation of function $\Delta I(D)$ appears — curve 1, and the dose of saturation D_a — curve 2 versus temperature of implantation

Zależności od temperatury implantacji: 1 — natężenia światła odbitego od próbki po wyjściu na nasycenie przebiegu $\Delta I(D)$; 2 — dawki, przy której osiąga się nasycenie D_a

sity of radiation-induced defects causing the transition from crystalline to disordered state, a greater dose of implanting ions is necessary [7].

In these investigations normal behaviour of $D_a(T)$, i.e. increase of D_a with temperature, is observed for temperatures lower than 120 K. In our opinion, in this temperature range the full amorphization takes place, while in higher temperatures, in spite of appearance of strong local disorder, only partial amorphization of implanted layer can occur.

As it was earlier shown [7], in case of simultaneous creation and annealing of defects, concentration of defects of i-type (N_i) can by the described by the following formula:

$$N_i(D,T,j) = \frac{W_i \times j}{K_i(T)} \times \left[1 - \exp\left[-\frac{D \times K_i(T)}{j}\right]\right], \tag{1}$$

where: $K_i(T) = \tau_0 \times \exp(-Em/kT)$ — the annealing kinetic coefficient; τ_0 — frequency of defect jumping; E_m — activation energy for annealing; W_i — number of defects created by one ion per length unit. For small doses of implanting ions this formula can be written as

$$N_i(D,T,j) - W_i \times D\,, \tag{2}$$

i.e. at early phases of implantation N_i does not depend on temperature and density of ion current.

For great doses the defect concentration N_i saturates and is given by:

$$N_i = N_i(D \to \infty, T, j) = \frac{W_i \times j}{K_i(T)}\,. \tag{3}$$

If the defect concentration N_i related to state of saturation is greater than the critical concentration C_{am} (necessary for transition into the disordered state) then, at the dose corresponding to this concentration, an amorphous state of implanted sample is reached.

At the temperature higher than 120 K not only decrease of D_a but also decrease of the change of light intensity reflected from implanted sample ΔI_n is observed (Figure 4).

It is known that the change of intensity of reflected light caused by ionic implantation of semiconductors, is associated with a change of their optical parameters n and α. The change of these parameters depends on density of radiation-induced defects created by ions [8]. Therefore, the decrease of ΔI_n observed at the temperatures $T > 120$ K confirms that density of defects N_i decreases with a rise of temperature in the implanted layer. It can also be shown by behaviour of ΔI as a function of dose at temperatures $T > 120$ K (Figure 2).

Increase of the temperature results in decrease of N_i and for sufficiently high temperature, for which $N_i < C_{am}$, full amorphization state cannot be accomplished for any dose of implanted ions. In our investigations we clearly deal with this case at temperatures greater than 120 K. Under these circumstances ($T > 120$ K), when in our opinion the full amorphization does not occur, initial parts of the curves $\Delta I = f(D)$ for different temperatures of implantation overlap (Figure 2, curves -2-5). This fact agrees with our preassumptions based on a model of simultaneous creation and annealing of defects, particularly with the deduction that for small doses of ions density of defects does not depend on temperature (see eq. 2).

Thus, the temperature 120 K, when D_a begins to decrease rapidly, can be treated as the maximum at which full amorphization of Cd Te implanted with Kr^+ can be obtained. Above this temperature only partial amorphization can take place.

In the narrow neighbourhood around this temperature ($\pm$ 5 K) the relationship $\Delta I(D)$ exhibits an oscillating character. According to above considerations and the previous works dealing with Si samples [9], this shape of obtained curve can be interpreted as a periodical cumulation and annealing of the most stable defect. The reconstruction of crystalline structure during implantation may take place when the value of energy activation for annealing E_{mi} becomes lower. The oscillating behaviour of defects concentration degree is observed in specific condition when defects concentration is extremely high and the temperature of implantation is a little bit lower then the temperature of thermal annealing. In these circumstances the effect of jumping recharging of defects [7, 10] cannot be neglected and in our opinion this fenomenon is responsible for shape of ΔI curve presented in Figure 3.

Under the assumption that ΔI_n is proportional to defect concentration, one can estimate, for instance, that for implantation carried out at temperature $T = 180$ K the sample can be amorphized to 90%. For higher temperatures the contribution of amorphized regions sharply decreases and finally, at $T = 300$ K, defect concentration becomes undetectable by use of our methods of measurement. Assumption that $\Delta I_n \sim N$ is expected to be chiefly justified for small values of ΔI_n i.e. at $T > 210$ K (see Figure 2). In this case, from equation 3 one can determine annealing activation energy for the defects, which are responsible for amorphization of CdTe crystals. Taking into consideration the accuracy of temperature and light intensity measurements, obtained value of $E_m = 0.10 \pm 0.02$ eV.

4. CONCLUSIONS

Using the *in situ* technique of studying defect creation processes in CdTe crystals implanted with Kr^+ ions, we have been able to discover that up to temperature of 120 K full amorphization of material takes place. At temperatures higher than this one, only partial amorphization of implanted material can occur due to annealing of a part of the defects during implantation. Dynamic equilibrium state of simultaneous creation and annealing of defects appears therefore in situation when amount of non annealed defects is not sufficient to achieve full amorphization of the sample. Annealing activation energy for the defects, accumulation of which leads to partial amorphization at the temperature $T > 120$ K has been estimated to be 0.10 ± 0.02 eV. This kind of defect can be regarded as the most stable in CdTe. The annealing activation energies of other possible defects have clearly smaller values and their contribution to the creation of disorder is negligible.

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STRESZCZENIE

Metodą *in-situ* zbadano kinetykę zmian koncentracji defektów w implantowanym CdTe w obszarze temperatur 100–300 K. W przypadku jonów $^{84}Kr^{+}$ o energii e = 90 keV oraz gęstości prądu jonowego 1 μA/cm^2 amorfizacja całkowita zachodzi przy temperaturach poniżej 120 K. Przy temperaturach powyżej 120 K zaobserwowano amorfizację częściową. Związane to jest z występowaniem równowagi dynamicznej pomiędzy tworzonymi podczas implantacji a wygrzewanymi defektami. Energia aktywacji wygrzewania termicznego defektów dla temperatur powyżej 120 K wynosi (0,10±0,02) eV.