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Ultrasonically stimulated temperature rise around dislocation: extended defect mapping and imaging

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Abstract. The nonuniform temperature distribution in a crystal surface during ultrasonic loading has been detected. This effect was associated with a sonic-stimulated temperature rise around dislocations and heating of the nonperfect regions of the samples investigated. The dislocation moved in an ultrasonic field was considered as a linear thermal source. We calculated the temperature distribution around dislocations and determined conditions of the discrete and continuous distribution of thermal sources for $Hg_{1-x}Cd_xTe$ alloys. We also discuss the possibility of using the investigated effect as the basis of a non-destructive technique for extended defect mapping and imaging in crystals.

PACS. 61.72.Lk Linear defects: dislocations, disclinations – 61.72.Hh Indirect evidence of dilocations and other defects (resistivity, slip, creep, strains, internal friction, EPR, NMR, etc.) – 81.70.Pg Thermal analysis, differential thermal analysis (DTA), differential thermogravimetric analysis

1 Introduction

The quality of microelectronics materials can be essentially changed by linear defects which naturally occur or that are introduced during technological processing. The control of defect distribution requires nondestructive and simple measurement methods for the investigation of defects. We propose a method that allows controlling the structural perfection by the controlling the ultrasonically stimulated temperature distribution in semiconductor crystals.

The physical origin of the ultrasonic oscillation effect on a crystal with dislocations is connected with intensive sonic-dislocation interaction, which can be explained by the vibrating string model of Granato-Luecke [1]. Such interaction has resulted in an effective transformation of the absorbed ultrasonic energy into the internal vibration states of the crystal stimulating defect reactions [2–6].

In this paper we present the results of a sonic-stimulated temperature rise investigation and discuss the application of such an effect.

2 Experimental procedure and results

N-type $Hg_{1-x}Cd_xTe$ (MCT) alloys with $x = 0.2$ and electron concentration $n_0 = (3 \div 5) \times 10^{14}$ cm^{-3} at 77 K were the subject of the investigation. The samples were cut from a single-crystal ingot grown by the Bridgman method. The linear dimensions of the samples after polishing and chemical etching were 8×2 mm^2 and the thickness was about 1 mm. The dislocation density N_{DIS} was controlled by the optical microscope NV2E (Carl Zeiss Jena), its value varies from 10^8 m^{-2} to 10^{11} m^{-2} for all investigated samples.

Longitudinal ultrasonic vibrations with frequency $f_{US} = (5 \div 7)$ MHz and intensity $W_{US} < 0.5$ W/cm^2 were generated by a $LiNbO_3$ transducer (35° Y-cut) and fed to the sample. The pre-threshold intensity regime was used. Switching off the ultrasonic loading led to a relaxation of all sample parameters to their original value in 10^3 s.

The effect of the ultrasonic loading manifests itself in an increase of the electron concentration in the impurity conductivity temperature range ($T < 120$ K) for all samples and in stimulated heating. The first phenomenon was described and analyzed elsewhere [6]. As for second effect, we placed several thermocouples along the investigated samples and detected the nonuniform macroscopic temperature distribution in their surface during *in situ* ultrasonic loading. The value of the sonic-stimulated temperature deviation from the average temperature in crystal was $10 \div 20$ K at an ultrasonic intensity $W_{US} < 0.5$ W/cm^2 (see Table, samples N1-N3).

We performed chemical selective etching of the samples and determined by optical microscope investigation that an inhomogeneous distribution of extended crystal defects such as dislocations is characteristic for the investigated samples. The average value of N_{DIS} varies from 10^9 m^{-2} to 10^{10} m^{-2} and the sonic-stimulated heating is observed

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Table 1. Parameters of investigated n-$Hg_{1-x}Cd_xTe$ crystals: N_{DIS} is dislocation density, d is the average distance between dislocations, ΔT is the sonic-stimulated temperature deviation from the average temperature in crystal.

Sample	N_{DIS}, m^{-2}	d, μm	ΔT, K
1	3×10^9	17	10
2	10^9	30	20
3	10^{10}	10	18
4	10^8	100	0
5	2×10^8	70	0
6	$\sim10^{12}$	1	0

in nonperfect regions with $N_{DIS} > 10^{11}$ m^{-2}. Figure 1a shows the dislocation image for such samples.

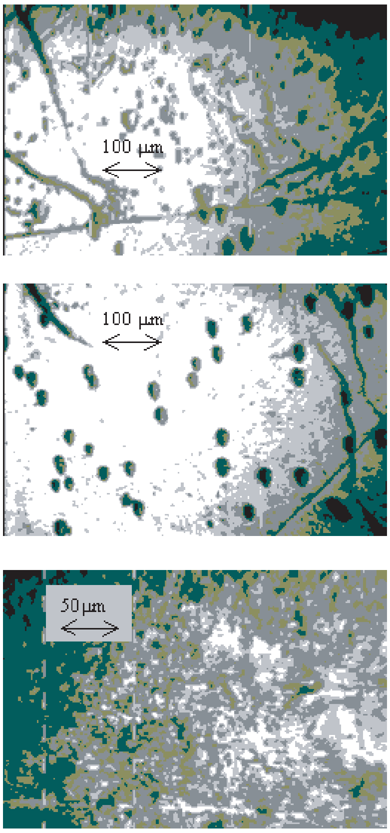

Fig. 1. The optical dislocation image of typical investigated samples of MCT crystal.

However, for samples with $N_{DIS} \sim 10^8$ m^{-2} (N4 and N5 from the Table) and uniform distribution of dislocations (see the dislocation image in Figure 1b) the macroscopic effects of sonic-stimulated heating was not detected. Finally, we investigated samples with mechanically produced damage layer with $N_{DIS} \sim 10^{12}$ m^{-2} (Figure 1c, N6 from the Table). The total heating of such samples during ultrasonic loading took place.

3 Discussion

We suggest that the physical origin of the nonuniform heating of the crystal is a selective absorption of the ultrasonic energy at dislocations. According to the Granato-Luecke model the dislocation moves in an ultrasonically loaded crystal as a vibrating string and periodical compression and expansion of the crystal around the dislocation takes place. During fast ultrasonic deformation, a vast amount of energy is put into the material during a relatively short period of time. Through the damping of dislocation motion by electrons and phonons the kinetic energy of a dislocation is dissipated into heat [7]. Since the processing time (period of ultrasonic wave is $\sim 10^{-7}$ s) is shorter than the relaxation time of sonic-stimulated heating, the heat may not have sufficient time to dissipate throughout the sample or to radiate into the environment. So, the temperature around dislocations can become considerably high.

We consider the dislocation moved in an ultrasonic field as a linear thermal source. The temperature distribution around dislocation line L can be written as:

$$T = T_0 + \int_t d\tau \int_L \frac{W_0}{\rho c} G dl. \tag{1}$$

In the above expression, $G(r,t)$ is Green function of the point thermal source, W_0 is the dissipated ultrasonic energy, ρ is the crystal density, C is the crystal heat, T_0 is an average equilibrium temperature in the crystal. If $L \to \infty$ and $t \to \infty$, the stationary temperature field around dislocation moved with velocity v along x-direction is:

$$T(x,z) = T_0 + \frac{W_0}{2\pi\chi} \exp\left(\frac{|x|}{R_0}\right) K_0\left(\frac{r}{R_0}\right)$$
$$r = \left(x^2+z^2\right)^{1/2} \tag{2}$$

where χ is thermal conductivity, K_0 is the zeroth order modified Bessel function, $R_0 = 2\chi/\rho C v$. Dislocation line is normal to plane xz. The regularity of the temperature distribution around dislocation for cases $r << R_0$ and $r >> R_0$ can be written as:

$$T = T_0 + \frac{W_0}{2\pi\chi} \ln\frac{R_0}{r}, \tag{3}$$

and

$$T = T_0 + \frac{W_0}{2\pi\chi}\left(\frac{\pi R_0}{2r}\right)^{1/2} \exp\left(-\frac{x+r}{R_0}\right), \tag{4}$$

accordingly. At $r > R_0$ the temperature value decreases exponentially and as consequence R_0 can be considered as a stationary heating radius of the dislocation. If the average distance between dislocations d exceeds the doubled heating radius R_0 the discrete distribution of thermal sources is realized and imaging observation of separate dislocations is possible. Otherwise, the thermal source distribution is continuous.

Figure 2 shows the temperature distribution around two dislocations during ultrasonic loading calculated

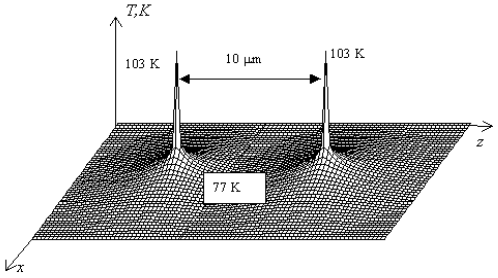

Fig. 2. Sonic-stimulated temperature distribution around two dislocation lines calculated by (3): equilibrium crystal temperature is T_0=77 K (in the plane XZ), sonic-stimulated temperature increase is $\Delta T = T - T_0$=25 K, intensity of the ultrasonic loading is W_{US}=0.4 W/cm^2.

by (3) for the discrete distribution of thermal sources $d = 10\ \mu$m<< $2R_0$ in MCT crystal. The calculated value of the temperature rise ($\sim$ 25 K) is in a good agreement with experimental one ($10 \div 20$ K).

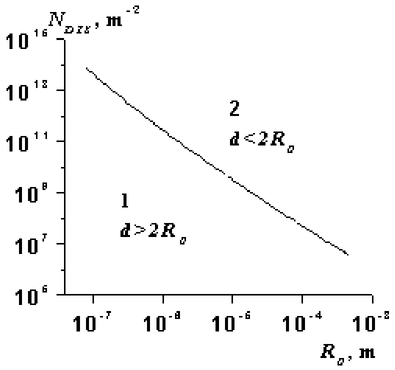

Fig. 3. The region of the discrete (1) and continuous (2) character of thermal source distribution.

Figure 3 shows regions of discrete (1) and continuous (2) distribution of thermal sources separated by $d = 2R_0$ regularity and allows to determine the limit value of the average dislocation density. The heating radius of the thermal source for some semiconductor crystals was determined by expression $R_0 = 2\chi/\rho C v$ if the dislocation velocity v is $0.01 v_{aw}$ [8], where v_{aw} is the velocity of acoustic wave. The value of R_0 and the critical value of N_{DIS} corresponding to the limit of the discrete distribution of thermal sources are presented in Table 2.

As we determined, the discrete character of thermal source distribution will be realized for MCT solid solutions up to dislocation density $N_{DIS} < 10^{11}$ m^{-2}. Really, for samples N4 and N5 with $N_{DIS} \leq 10^8$ m^{-2} the macroscopic effect of sonic-stimulated heating was not detected whereas the total heating of sample N6 with $N_{DIS} \sim 10^{12}$ m^{-2} took place. We also observed some "hot" regions with $N_{DIS} \geq 10^{11}$ m^{-2} for MCT samples N1–N3 with nonuniform dislocation distribution.

Table 2. The thermal diffusivity ($\chi/\rho C$), the velocity of acoustic wave (v_{aw}), the heating radius (R_0) and critical density (N_{DIS}) of dislocation for some semiconductor crystals.

Crystal	$\chi/\rho C$, m^2/c	v_{aw}, m/c	R_0, μm	N_{DIS}, m^{-2}
$Hg_{0.8}Cd_{0.2}Te$	0.8×10^{-5}	3.2×10^3	0.5	$<10^{11}$
CdTe	0.7×10^{-5}	2×10^3	0.7	$<10^{11}$
GaAs	5.3×10^{-5}	3×10^3	3.5	$<10^{10}$
Ge	3.5×10^{-5}	5×10^3	1.4	$<10^{10}$
Si	2×10^{-5}	10^4	0.4	$<10^{11}$

MCT alloy is the main material for infrared ($8 \div 14\ \mu$m) detector technology. The quality and reliability of MCT based devices can be dramatically changed by structural defects such as dislocations and low angle grain boundaries. We think that the investigated effect of ultrasonically stimulated heating can be used for nondestructive imaging and mapping of structural defects in solids and for MCT crystals such method is especially effective through essential sensitivity this material to sonic vibration [5,6].

4 Conclusions

In this paper we report the results of an experimental study of an ultrasonically stimulated thermal effect in $Hg_{0.8}Cd_{0.2}Te$ crystals. The nonuniform temperature distribution in crystal surface during ultrasonic loading was detected. This effect was associated with a sonic-stimulated temperature rise around dislocations and heating of the nonperfect regions of the investigated samples. It is possible to use the investigated effect as the basis for a non-destructive technique for structural perfection control of crystals.

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