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Periodic structure formation in GaAs near-surface layer by laser beam with diffraction modulated intensity

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The method of grids was used to calculate thermoelastic stresses on GaAs surface caused by a non-destructive laser exposure with diffraction spatial intensity modulation from a screen with a rectangular cut-out. The structure of irradiated near-surface layers of samples was studied using optical method. Periodic insular structures formed due to diffusive redistribution of defects were revealed using the level-by-level chemical etching.

Методом сеток проводился расчет термоупругих напряжений на поверхности GaAs, возникающих при неразрушающем лазерном облучении с дифракционной пространственной модуляцией интенсивности от непрозрачного экрана с прямоугольным вырезом. Оптическим методом исследовалась структура облученных приповерхностных слоев кристаллов. Послойным химическим травлением выявлены периодические островковые структуры, образованные в результате диффузионного перераспределения дефектов.

The great interest in study of nano-sized structures [1, 2] stimulates the elaboration of promising methods for creation of quantum points (QP). The ways are known to obtain homogeneous arrays of three-dimensional QP with cross-sectional regularity in the InAs–GaAs system by means of molecular beam epitaxy and gas-phase epitaxy from vapors of organometallic compounds [3, 4]. The QP creation using the self-organization phenomenon on a crystal surface under irradiation by a laser pulse appears to be a promising technique [5, 6]. In such technology, the parameters of generated structures are defined by the substrate properties, therefore, there are difficulties in control of periodicity and sizes of individual structure elements. Usage of different techniques for spatial modulation of the laser exposure sets unambiguously the energy distribution on the sample surface and provides the effective periodicity control of created structures [7–10].

In this work, studied is a non-destructive mechanism of periodic defective structures formation by a laser radiation with diffraction-modulated intensity. Such irradiation creates laterally periodic gradients of thermoelastic stresses in the crystal near-surface layer. These stresses cause diffusive redistribution and grouping of point defects [11]. The field of thermoelastic stresses is calculated by computer simulation of diffracted laser radiation absorption by the crystal surface. The intensity factor of the diffraction picture at the edge of a half-plane [12] is

$$\kappa = I/I_0 = \frac{[1/2 + \xi(\nu)]^2 + [1/2 + \eta(\nu)]^2}{2}, \quad (1)$$

where parameter $\nu = -x\,(2/(\lambda b))^{1/2}$; λ, the optical radiation wavelength; b, height of the half-plane edge above the irradiated surface. The Fresnel integrals look as

$$\xi = \int_0^{\nu} \cos(\pi u^2/2)du, \quad \eta = \int_0^{\nu} \sin(\pi u^2/2)du. \tag{2}$$

Here, du is normalized amplitude of the elementary vector of the light wave electric field strength; the integrands are its projections. The intensity factor of the diffraction picture at the edge of a screen parallel to the semiconductor surface and having a rectangular cut-out is calculated as product of intensity factors from two orthogonal half-planes forming the screen (Fig. 1, inset):

$$\kappa = \kappa_x(x) \cdot \kappa_y(y). \tag{3}$$

The light intensity gradient will have maximum values along the bisector of the rectangular cut-out (Fig. 1).

Thermoelastic fields arise in the near-surface semiconductor layer due to the diffraction-modulated irradiation. The method of grids was used to solve numerically the second order differential equation [13]

$$c\rho\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + g, \tag{4}$$

where c is specific heat; ρ, density of material; T, temperature; t, time; z, coordinate in the direction normal to the surface; k, heat conductivity; g, heat power generated in a unit volume of material due to absorption of the laser radiation. In a thin surface layer of depth h, the heat power is $g = hq_0\alpha$, where q_0 is the power of the diffraction-modulated irradiation (Fig. 1); α, light absorption coefficient of the surface. Approximations of experimental data were used to take into account the temperature dependence of c, k and α. The temperature of the sample undersurface was assumed to be constant.

When solving the equation by the method of grids, we have arranged the nodes on the coordinate plane $z(t)$ at a step h along the axis z and at a step τ along the time axis t. The nodes were numbered starting from the zero one, which in the initial instant is placed on the sample surface. Let the temperature in the node with coordinates $z = nh$ and $t = j\tau$ be T^j_n. The differential equation is changed by a difference equation [14]

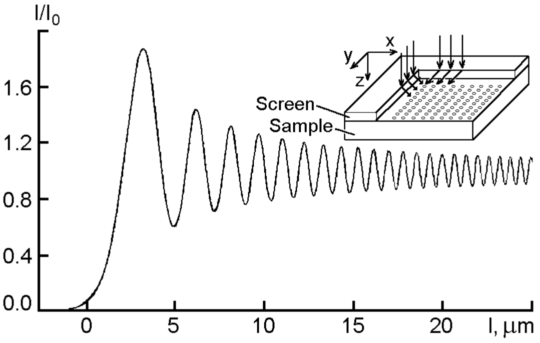

Fig. 1. Relative light intensity as a function of the distance from the edge of the screen projection along the bisector of the rectangular cut-out. Inset: scheme of irradiation.

$$c^j_n\rho\frac{T^{j+1}_n - T^j_n}{\tau} = k^j_n T^{j+1}_{n+1} - 2T^{j+1}_n + \frac{T^{j+1}_{n-1}}{h^2} + \\ + \frac{k^j_{n-1} - k^j_n}{h} \cdot \frac{T^{j+1}_{n+1} - T^{j+1}_n}{h} + g. \tag{5}$$

The boundary condition on the sample surface is the heat balance equation for the boundary layer of depth h. For the boundary where the laser radiation with a power density W is absorbed, we have

$$(T^{j+1}_0 - T^j_0)C^j_0\rho h = W\tau + k^j_0\tau(T^{j+1}_1 - T^{j+1}_0)/h. \tag{6}$$

There is no heat flow through the sample undersurface ($n = N$), that is why the equation of the heat balance looks as

$$(T^{j+1}_0 - T^j_0)C^j_0\rho h = W\tau + k^j_0\tau(T^{j+1}_1 - T^{j+1}_0)/h. \tag{7}$$

The initial condition sets the initial temperature distribution over the sample depth $T(x,0) = T_0 = 300$ K. When the sample is irradiated by a laser pulse of duration τ_p and when the the sample thickness $H = Nh > (k\tau_p/(c\rho))^{1/2}$, it is possible to consider the sample undersurface temperature during the time τ_p to be constant. For GaAs sample and laser pulse duration $\tau_p = 1$ ms, $H > 0.2$ mm. In that case, it is possible to use the condition $T^{j+1}_N = T_0$. The power density distribution in the laser beam $W = W_0\cos^2(\pi r/D)$ was close to Gaussian one, where W_0 is power density in the laser spot center; D, the spot diameter; r, distance from the spot center.

The distribution of the surface temperature maximum along the bisector of the rectangular cut-out for the GaAs sample subjected to a ruby laser pulse of 1 ms duration and energy density 12 J/cm^2 is shown in Fig. 2. In the area of interest, apart

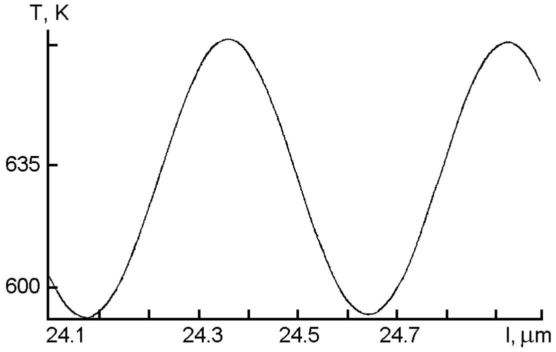

Fig. 2. Distribution of the surface temperature along the bisector of the rectangular cut-out.

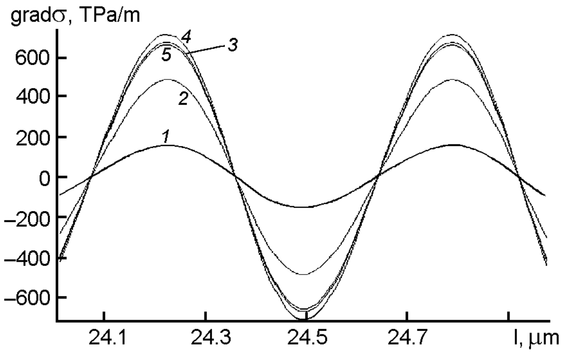

Fig. 3. Distribution of the thermoelastic stress gradient along the bisector of the rectangular cut-out.

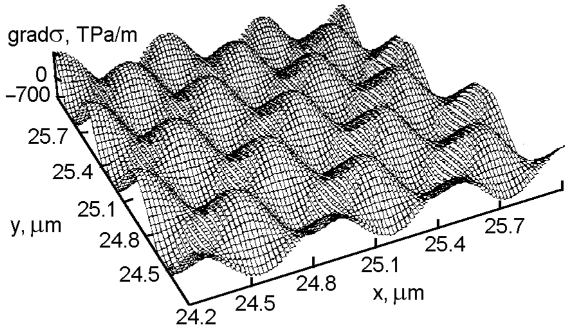

Fig. 4. Distribution of the thermoelastic stress gradient in the surface layer plane.

24 μm from the vertex of the rectangular cut-out along its bisector, the maximum energy density varied due to diffraction modulation within limits from 11.5 J/cm^2 up to 12.3 J/cm^2. The sample surface layer heated by the laser pulse lies on a cold subsurface layer, which hinders the heat expansion of the surface layer. Thus, the surface layer is subjected to a compressive strain. A thermoelastic stress $\sigma = E\beta(T - T_0)$ arises in the surface layer, where E is modulus of elasticity; β, linear thermal expansion coefficient. To the maximum temperature, the maximum stress corresponds, to the minimum temperature, the minimum one. The surface distribution of thermoelastic stresses repeats the temperature distribution. The minimum stress is equal to 463 MPa and the maximum one, to 507 MPa. The period of the thermoelastic stress gradient distribution along the bisector of the rectangular cut-out in area remote from the screen edge (Fig. 3) is equal to that of the surface temperature distribution (Fig. 2). The distribution of the thermoelastic stress gradient in the surface layer plane is shown in Fig. 4.

Samples of GaAs single-crystal, trademark AGChT-1-25a-1, with the (100), (110), and (111) planes prepared by chemical polishing were studied in experiment. The samples were irradiated by a ruby laser (λ = 0.694 μm) working in the free generation mode (τ = 1 ms). The pulse energy ≤350 mJ, the laser spot diameter was about 3.5 mm. The diffraction spatial modulation was provided by a screen with rectangular cut-out. The screen was placed on the sample surface in edge area of the laser spot, where the intensity is insufficient for melting and cracking. The value of energy density in this area 12 J/cm^2 was utilized for computer simulation of the process. The irradiation scheme is shown in the inset to Fig. 1.

To achieve maximum shear stresses, an out-of-focus laser beam was used [15]. No changes of the sample surface relief were noticed by optical methods in the zone irradiated with diffraction intensity modulation. After subsequent level-by-level metallographic etching in AB solution [16], a periodic structure (Fig. 5) characteristic of this kind of diffraction was revealed. The period of this structure coincides with theoretically calculated one (Fig. 3) and at the distance about 25 μm, it is equal to the irradiation wavelength. A similar periodic relief from the diffraction-modulated laser beam was observed before [17, 18], but in those experiments, the surface became damaged due to a local melting in the diffraction maxima. In our experiments, the power density was insufficient for melting. The inhomogeneous stress distribution on the surface creates a flow of vacancies along the compressive stress gradient [11]. A diffusive redistribution of point defects with formation of insular structure occurs in a

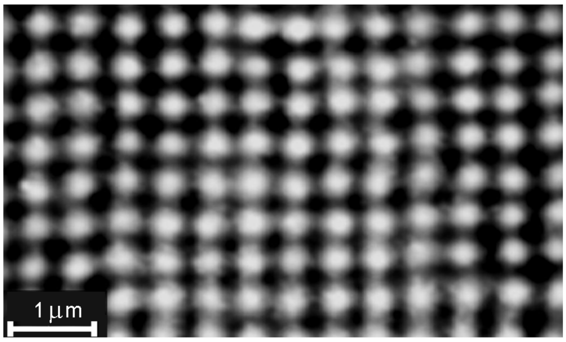

Fig. 5. A periodic relief revealed by chemical etching in GaAs surface layer irradiated by a laser pulse with a diffraction spatial modulation. The image is taken at the distance ~ 25 μm from the rectangular cut-out along the bisector.

near-surface semiconductor layer. In contrast to the previous experiments [17], such surface changes cannot be revealed in optical examinations without special chemical etching. The areas where defect concentration is higher are etched faster [19]. As a result, a periodic surface relief in the form of islands with diameter equal to half of the radiation wavelength is revealed in the near-surface layer. The structure remains stable at 20 °C. No noticeable changes of the relief were found after one-year storing of the irradiated samples.

It has been found that due to relaxation of thermoelastic stresses, no periodic relief is formed under the influence of high laser energy densities in the cracking zone. The similar point structures can be formed by laser irradiation through technological masks used in the chip manufacturing. A short-wave laser radiation must be used for obtaining QP of smaller size. The proposed technique can be used for creation of quantum dimension device structures. The possible redistribution in the system of point defects stimulated by the radiation and depending from the quantum energy, power and duration of irradiation, concentration and nature of the doping agent in the single crystal must be taken into account when laser technology of device manufacturing is used. Investigations of this problem are reported in [20, 21]. The formation opportunity of device structures as the "buried" Schottky barriers formed by As clusters in a n-GaAs matrix is surveyed in [22].

References

1. S.V.Gaponenko, in: Nanostructure Materials and their Properties, Materials of the Seminar "Nanostructure materials - 2000€, Minsk (2000), p.68 [in Russian].
2. Zh.I.Alferov, *Usp.Fiz.Nauk*, **172**, 1068 (2002).
3. N.N.Lebentsov, M.Grundmann, N.Kirstaedter, in: Proc. of 22nd Intern. Conf. on the Physics of Semiconductors, Vancouver, Canada, (1994), v.3, Singapore: Word Scientific Publ. Co. (1995), p.1855.
4. Zh.I.Alferov, N.Yu.Gordeev, S.V.Zaitsev, *Fiz. Tekhn.Poluprov.*, **30**, 357 (1996).
5. S.V.Vintsents, A.V.Zaitseva, G.S.Plotnikov, *Fiz.Tekhn.Poluprov.*, **37**, 134 (2003).
6. S.V.Vintsents, A.V.Zaitseva, V.B.Zaitsev, *Fiz. Tekhn.Poluprov.*, **38**, 257 (2004).
7. C.E.Nebel, S.Christiansen, H.P.Strunk, *Phys. Status Solid. (A)*, **166**, 667 (1998).
8. G.Aichmayr, D.Toet, M.Mulato, *Phys.Stat. Solid.(A)*, **166**, 659 (1998).
9. G.Aichmayr, D.Toet, M.Mulato, *J.Non-Cryst. Solids*, **227–230**, 921 (1998).
10. M.K.Kelly, J.Rogg, C.E.Nebel, *Phys.Stat. Solid. (A)*, **166**, 651 (1998).
11. V.A.Nadtochiy, V.P.Alyokhin, *Fiz.Khim.Obrab. Mater.*, **4**, 27 (2004).
12. M.Born, E.Wolf, Principles of Optics, Pergamon Press, Oxford (1964).
13. V.A.Nadtochiy, N.N.Golodenko, A.Z.Kalimbet, *Fiz.Khim.Tverd.Tila*, **4**, 556 (2003).
14. A.V.Dvurechenskiy, G.A.Kachurin, V.E.Nidayev, Pulse Annealing of Semiconductor Materials, Nauka, Moscow (1982) [in Russian].
15. V.A.Nadtochiy, V.P.Alyokhin, N.K.Nechvolod, *Fiz.Khim.Obrab.Mater.*, 4, 9 (2003).
16. Z.Yu.Gotra, Technology of Microelectronic Devices: Reference Book, Radio i Svyaz, Moscow (1991) [in Russian].
17. A.V.Demchuk, N.I.Danilovich, V.A.Labunov, *Fiz.Khim.Obrab.Mater.*, **4**, 84 (1988).
18. P.K.Kashkarov, Yu.V.Timoshenko, *Poverkhnost'*, **6**, 5 (1995).
19. V.Nadtochy, M.Golodenko, D.Moskal, *Functional Materials*, **11**, 40 (2004).
20. V.D.Andreeva, N.G.Dzhumamukhambetov, A.G.Dmitriev, *Fiz.Tekhn.Poluprov.*, **25**, 1624 (1991).
21. S.B.Plyatsko, *Fiz.Tekhn.Poluprov.*, **34**, 1046 (2000).
22. M.G.Mil'vidskiy, V.V.Chaldyshev, *Fiz.Tekhn. Poluprov.*, **32**, 513 (1998).

Формування періодичної структури у приповерхневому шарі GaAs лазерним променем з дифракційною модуляцією інтенсивності

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Методом сіток виконано розрахунок термопружних напружень на поверхні GaAs, що виникають при неруйнівному лазерному опроміненні з дифракційною просторовою модуляцією інтенсивності від непрозорого екрана з прямокутним вирізом. Оптичним методом досліджувалася структура опромінених приповерхневих шарів кристалів. Пошаровим хімічним травленням виявлені періодичні острівцеві структури, що утворені внаслідок дифузійного перерозподілу дефектів.