DEEPLY PENETRATING ELASTIC AND COUPLED SURFACE WAVES IN CRYSTALS

YU. A. KOSEVICH

All-Union Surface and Vacuum Research Centre, Moscow 117334, USSR

ABSTRACT. Deeply penetrating elastic and coupled surface waves (DPSW) in crystals are treated. It is shown that the parameters of the DPSW are very sensitive to near-surface disturbances of the acoustic and electromagnetic parameters of the crystal, which is essential for the technical applications of DPSW.

0. An interesting type of surface waves (SW), which has been the subject of recent fundamental and applied investigations, is SW with a penetration depth much greater than the wavelength (DPSW). These waves occupy an intermediate position between bulk and SW with penetration depth of the order of the wavelength, such as the Rayleigh SW in isotropic elastic media. The property of deep penetration draws considerable attention to the DPSW, because in some cases, particularly in technical applications, they can combine advantages of both bulk and surface waves.

In this report we demonstrate that the DPSW present a wide class of elastic, electromagnetic and coupled waves in crystals. We consider the following DPSW: 1. the ordinary and generalized Rayleigh and Gulyaev- Bleustein SW in highly anisotropic crystals and piezoelectrics; 2. the coupled magnetoacoustic and magnetoelectroacoustic SW in piezomagnetic and segnetomagnetic crystals; 3. the coupled magnetoelastic SW in metals with finite conductivity and in elastic dielectric medium with a 2D electron layer in an external magnetic field; 4. the internal elastic and electromagnetic SW, localized near a 2D crystal defect. We show that the parameters of the DPSW (such as the penetration depth) are very sensitive to near-surface disturbances of the acoustic and electromagnetic properties of the crystal, which is essential for the technical application of DPSW.

1. We show that the DP Rayleigh waves exist in crystal if and only if the bulk transverse elastic waves are highly anisotropic in the sagittal plane. Therefore the main properties of Rayleigh and Gulyaev-Bleustein DPSW can be analysed in highly anisotropic cubic (or tetragonal) crystals. These crystals are compounds in the vicinity of the proper ferroelastic or ferroelectric-ferroelastic phase transition, which is accompanied by a softening of one of the bulk transverse acoustic modes (such as Nb_3Sn, V_3Si, TeO_2, KDP, Rochelle salt, etc.). The Rayleigh waves propagating in the direction [010] on the boundary plane (100) of a cubic (or tetragonal) crystal for $\eta \ll 1$ ($\eta = 2C_{66}/(C_{11}-C_{12})$, C_{ik} being the elastic moduli) are ordinary DPSW, i.e., with amplitude decreasing monotonically into the bulk of the crystal, and for $\eta \gg 1$ are generalized DPSW, i.e., decreasing with oscillations [1, 2]. The parameter of inverse penetration depth (PIPD) p of a main component of the Rayleigh wave for $\eta \ll 1$ is of the form $p_1 = [C_{66}C_{11}/(C_{11}^2 - C_{12}^2)]^{3/2} \equiv \delta^{3/2} \sim \eta^{3/2}$ and for $\eta \gg 1$ of the form $p_{1,2} = 1/(2\eta)(1 + C_{66}/C_{11} \pm i[1 - 1/(2\eta)(1 + C_{66}/C_{11})]$ with elastic displacements having the form $\tilde{U}_{1,2} \sim \exp(ikx + pkz - i\omega t)$; ω, k are the frequency and wave number. Gulyaev-Bleustein waves propagating in the direction [110] on the boundary plane (110) of cubic T_d (or tetragonal D_{2d}) piezoelectric for $K^2 \ll 1$ are ordinary DPSW and for $K^2 \gg 1$ are generalized DPSW [3, 4]. Here, $K^2 = 4\pi e_{14}^2/(C_{44}^E \in \varepsilon^4)$ is the parameter of electromechanical coupling, and $K^2 = \tilde{K}^2/(1 - \tilde{K}^2)$, where $\tilde{K}^2 < 1$ is the usual coefficient of electromechanical coupling. Near the proper ferroelectric-ferroelastic phase transition the parameter K^2 diverges as $K^2 \sim (T - T_C)^{-1}$ and the coefficient $\tilde{K}^2 \to 1$. The PIPD p of the elastic field of the Gulyaev-Bleustein wave on the metallized boundary is of the form: $p_1 = K^2$ for $K^2 \ll 1$, $p_{1,2} = 1/(2K^2) \pm i$ for $K^2 \gg 1$. We have analyzed the transition from ordinary to generalized SW on the boundary of the crystal on a change in the anisotropy parameter η for Rayleigh waves and a change in the electro-mechanical parameter K^2 for Gulyaev-Bleustein waves. We also studied the SW in the case of degenerate roots of the characteristic equation for the bulk vibrations ($p_1 = p_2$). Taking into account capillary effects (surface stress tensor $g_{\mu\nu}$, excessive surface moduli $h_{\alpha\beta\gamma\delta}$ and surface mass ρ_s) we obtain the PIPD p of the elastic field of the DPSW in the form: $p_1 = \delta^{3/2} + K\delta(\rho_s/\rho - g_1/C_{66})$ for the Rayleigh SW in the case $\delta \ll 1$, $p_1 = K^2 + k[\rho_s/\rho - (g_1 + h_{66})/C_{44}]$ for the Gulyaev-Bleustein SW in the case $K^2 \ll 1$, i.e., the influence of the near-surface disturbances on the properties of the DPSW intensifies with growing penetration depth of the SW (generated by decreasing the parameters and K^2 consequently) [2, 5].

2. Piezomagnetic and linear magnetoelectric effects may exist in crystals with magnetic structure. Within the framework of the macroscopic description the piezomagnetic effect is analogous to the piezoelectric one, so in piezomagnetic crystals (antiferromagnetics) we may expect the existence of coupled magnetoacoustic SW. In the tetragonal piezomagnetics CoF_2 and MnF_2, shear SW may exist on the boundary plane (110) in the direction [110], [3, 6]. Since the parameter of magnetomechanical coupling $\Lambda^2=4\pi\beta_{14}^2/(\mu C_{44})$ in the above mentioned crystals is rather small, the magnetoacoustic SW in them are DP, the PIPD p of the elastic field of the SW is of the form $p_1=\Lambda^2/(1+\mu_1)\ll 1$. The DP coupled magnetoelectroacoustic SW can exist in segnetomagnetic crystals, which present both piezoelectric, magnetoelectric and magnetoelastic effects [7]. Such SW is accompanied by quasistatic electric and magnetic fields.

3. The magnetic Lorentz force, beside pure elastic forces, acts on the vibrating element of the conducting medium in an external magnetic field $\vec{H}_0$. We have studied the shear DPSW, caused by the Lorentz force, in 3D metals with finite conductivity and in elastic dielectric medium with 2D electron layer in the case of quantum Hall effect [8–12]. The PIPD p of the elastic field of weakly damping DPSW propagating in the direction $\vec{H}_0 \| [110]$ on the boundary (100) of cubic metallic crystal is of the form

$$p_1=(1+i)\,H_0^2/(4\pi C_{44})\,\{\lambda_{\mathrm{D}}\,\rho\omega^2 c^2/4\pi\,(C_{11}-C_{12})\}^{1/2}$$

(λ_{D} is the specific dissipative resistance of the metal). For this mutual orientation of the vectors $\vec{k}$ and $\vec{H}_0$ the parameter p_1 of the SW attains its maximum. When the 2D Hall conductivity of the electron layer in a transverse $\vec{H}_0$ is greater than the dissipative conductivity, the 2D layer in elastic dielectric medium (like the inversion layer in a heterostructure) generates a practically pure shear DPSW, localized near the 2D electron layer.

4. We have analysed the main properties of the three types of longwavelength DPSW, localized near a plane 2D crystal defect (such as the plane defect of stacking fault type, twinning boundary), taking into account capillary effects [13, 14]. We have shown that allowance for jumps in both surface stress and elastic displacements on the 2D crystal defect is essential for the correct macroscopic description of the elastic SW. We obtained a system of macroscopic boundary conditions for Maxwell's equations on the plane of a 2D polarizable defect layer in dielectric crystal, which takes into account the jumps in tangent magnetic and electric fields. Using the equations of macroscopic electrodynamics of the 2D dielectric layer we have demonstrated the possibility of the existence of *two* types of longwavelength electromagnetic DPSW (of the TE and TM polarizations), localized near the plane of a 2D polarizable layer. The PIPD p of the elastic and electromagnetic SW near the 2D crystal defect are of the same order $p\sim dk\ll 1$ (d is the effective thickness of the 2D defect of order of the interatomic spacing). Electromagnetic SW near a 2D crystal defect with locally enhanced polarizability are analogous to the two longwavelength fundamental (gapless) modes of a symmetric waveguide.

REFERENCES

[1] A.M. Kosevich, Yu.A. Kosevich and E.S. Syrkin, *Sov. Phys. JETP* **61** (1985), 639.
[2] Yu.A. Kosevich and E.S. Syrkin, *Sov. Phys. JETP* **62** (1985), 1282.
[3] Yu.A. Kosevich and E.S. Syrkin, *Fiz. Tverd. Tela* **28** (1986), 248.
[4] Yu.A. Kosevich, O.Yu. Serdobol'skaja and E.S. Syrkin, *Ferroelectrics* **75** (1987), 409.
[5] Yu.A. Kosevich and E.S. Syrkin, *Pis'ma Zh. Techn. Fiz.* **13** (1987), 1435.
[6] M.I. Kaganov and Yu.A. Kosevich, *Poverkhnost'* No. 8 (1986), 148.
[7] Yu.A. Kosevich, *Fiz. Tverd. Tela* **27** (1985), 193.
[8] Yu.A. Kosevich, *JETP Lett.* **45** (1987), 630.
[9] Yu.A. Kosevich and E.S. Syrkin, *Pis'ma Zh. Techn. Fiz.* **14** (1988), 1375.
[10] Yu.A. Kosevich and E.S. Syrkin, *Akust. Zh.* **34** (1988), 879.
[11] Yu.A. Kosevich and E.S. Syrkin, *J. Phys.* **C21** (1988), L257.
[12] Yu.A. Kosevich and E.S. Syrkin, *Fiz. Nizk. Temp.* **14** (1988), 85.
[13] Yu.A. Kosevich and E.S. Syrkin, *Phys. Lett.* **122A**, (1987).
[14] Yu.A. Kosevich and E.S. Syrkin, *Kristallografiya* **33** (1988), 1339.