P:10 Quantized acoustic-phonon modes in a non-piezoelectric nanowaveguide

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To reach the terahertz frequency domain, size reduction of the resonator down to a few nanometers is required. Here, for the first time, we take the necessary step of quantizing the acoustic shear modes in an isotropic non-piezoelectric waveguide structure, using the general unquantized equations presented earlier by Auld [1]. In this work, a thin plate of infinite length with the thickness of ' and width of is considered. To avoid the spurious frequency responses produced by other modes of the structure which rests very close to the desired resonance, the plate is thickened in the area where energy trapping is to be realized (Fig. 1). The thickened region has the thickness of t with the lateral dimension of w', and to confine the resonance fields near the thickened part and far from the edges of the plate; $w' \cong t$is assumed. In this ridged waveguide, the shear horizontal (SH) waves are polarized in x direction and propagating along the z-axis. By adopting the notations in [1], and considering the fundamental mode of n = 1 and m = 1 along with the assumption of $t \cong t'$, the unquantized acoustic-mode displacements and stress fields can be written as follows:

$$U_x = \begin{cases} \cos\left[\frac{\pi}{t'}\left(y+\frac{t'}{2}\right)\right] Ce^{\gamma_1 z}, & z < -\frac{w'}{2} \\ \cos\left[\frac{\pi}{t'}\left(y+\frac{t'}{2}\right)\right] \left(Ae^{-i\beta_1 z} + Be^{+i\beta_1 z}\right), & -\frac{w'}{2} < z < \frac{w'}{2} \\ \cos\left[\frac{\pi}{t'}\left(y+\frac{t'}{2}\right)\right] De^{-\gamma_1 z}, & z > \frac{w'}{2} \end{cases} \tag{1}$$

$$\beta_1^2 = \left(\frac{\omega}{V_s}\right)^2 - \left(\frac{\pi}{t}\right)^2, \tag{2}$$

$$T_{xz} = \begin{cases} \gamma_1 . c_{44} . \cos\left[\frac{\pi}{t'}\left(y+\frac{t'}{2}\right)\right] Ce^{\gamma_1 z}, & z < -\frac{w'}{2} \\ -i\beta_1 c_{44} . \cos\left[\frac{\pi}{t'}\left(y+\frac{t'}{2}\right)\right] \left(Ae^{-i\beta_1 z} - Be^{+i\beta_1 z}\right), & -\frac{w'}{2} < z < \frac{w'}{2} \\ -\gamma_1 . c_{44} . \cos\left[\frac{\pi}{t'}\left(y+\frac{t'}{2}\right)\right] De^{-\gamma_1 z}, & z > \frac{w'}{2} \end{cases} \tag{3}$$

where $\beta 1$ is the wave vector of the wave, $\gamma_1 = -i\beta_1$, A,B,C and D are the four unknown wave amplitudes. By solving the boundary conditions, where U_x and $T_{xz}$are continuous at z= $\pm \frac{w'}{2'}$ for two cases of (i) even symmetry modes (B= A,D= C) and, (ii) odd symmetry modes (B=−A,D= −C) with the assumption of $t = t'$, the number of unknown wave amplitudes can be reduced. Now, by following the quantization procedure described by Stroscio et al. in [2], the normalization constant of the SH acoustic modes can be obtained as follows:

$$\frac{1}{tw}\left(\int_{-\frac{t'}{2}}^{-\frac{t}{2}} dy \int_{-\frac{w}{2}}^{-\frac{w'}{2}} dz \{U_X . U_X^*\} + \int_{-\frac{t}{2}}^{\frac{t}{2}} dy \int_{-\frac{w'}{2}}^{\frac{w'}{2}} dz \{U_X . U_X^*\} + \int_{\frac{t}{2}}^{\frac{t'}{2}} dy \int_{\frac{w'}{2}}^{\frac{w}{2}} dz \{U_X . U_X^*\}\right) = \frac{\hbar}{2m\omega} \tag{4}$$

where m is the atomic mass and $\omega$is the wave angular frequency. Finally, by performing the integration indicated in Eq. 4, the amplitude C is found to be,

$$C = \sqrt{\frac{\hbar}{2m\omega}} \cdot \frac{1}{\sqrt{\frac{1}{2w\gamma_1}\left(e^{-w'\gamma_1} - e^{-w\gamma_1}\right) + \frac{w'\gamma_1^2}{4w\beta_1^2} \cdot e^{-w'\gamma_1} \cdot \left(\frac{1 + \frac{\sin(\beta_1 w')}{\beta_1 w'}}{\sin^2\left(\frac{\beta_1 w'}{2}\right)}\right)}}, \quad (5)$$

for the even symmetry modes and

$$C = \sqrt{\frac{\hbar}{2m\omega}} \cdot \frac{1}{\sqrt{\frac{1}{2w\gamma_1}\left(e^{-w'\gamma_1} - e^{-w\gamma_1}\right) + \frac{w'\gamma_1^2}{4w\beta_1^2} \cdot e^{-w'\gamma_1} \cdot \left(\frac{1 - \frac{\sin(\beta_1 w')}{\beta_1 w'}}{\cos^2\left(\frac{\beta_1 w'}{2}\right)}\right)}} \quad (6)$$

for the odd symmetry modes.

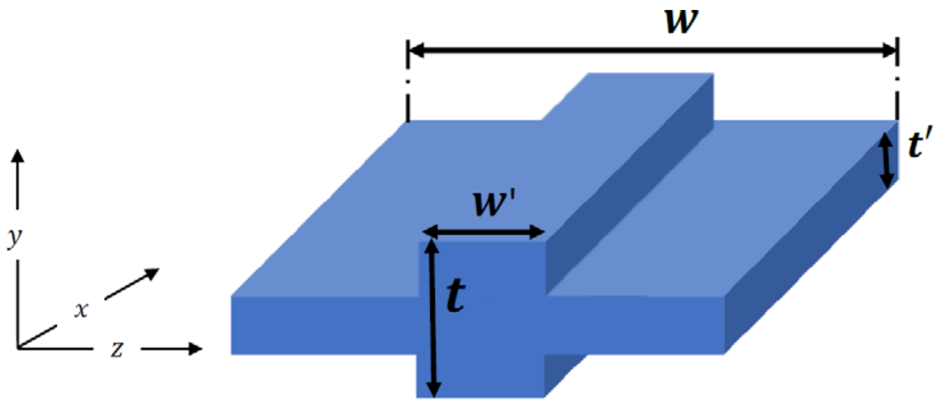

Fig. 1: Acoustic SH mode non-piezoelectric nanowaveguide designed by thickening the central region of the thin plate.

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[1] B. A. Auld, Acoustic fields and waves in solids, ISBN: 978-5-88501-343-7 (1973).
[2] Stroscio et al., Phys. Rev. B 48, 1936–1938, doi: 10.1103/PhysRevB.48.1936 (1993).