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Carrier-induced dynamic backaction in GaAs micromechanical resonators

Hajime Okamoto[1], Daisuke Ito[1,2], Koji Onomitsu[1], Haruki Sanada[1], Hideki Gotoh[1], Tetsuomi Sogawa[1] and Hiroshi Yamaguchi[1,2]

[1]NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan
Phone: +81-46-240-2522 E-mail: hajime@nttbrl.jp
[2]Tohoku university, Department of Physics, Sendai, Miyagi 980-8578, Japan

1. Introduction

Dynamic backaction in micromechanical resonators has recently become a focus of research in physics.[1-4] Cavity-induced opto-mechanical coupling provides backaction on the mechanical motion while modifying the resonance frequency and the quality factor of the resonators. Such opto-mechanical coupling is, however, not based on the optical properties of semiconductors but on the radiation pressure[1-3] and photothermal pressure.[4] If opto-mechanical coupling via carrier excitation can be realized, applications of micromechanical resonators will be further expanded because of the high controllability, high transduction efficiency, and integration capability with semiconductor-based opto-electronic devices. It will also provide an alternative tool for studying strain effects and the carrier-related energy relaxation mechanism in semiconductors. Here, we demonstrate vibration amplification, damping, and self-oscillations in GaAs microcantilevers induced by opto-mechanical coupling through carrier excitation. This phenomenon is caused by the carrier-induced piezoelectric backaction, which is generated by the photovoltaic effect.

2. Experimental

The cantilever is shown in Fig. 1(a). It consists of Si-doped *n*-GaAs and undoped *i*-GaAs layers, where both [110] and [-110]-oriented cantilevers were prepared to study the effect of orientation on the mechanical vibration [Fig. 1(b)].[5] The cantilevers were set in a vacuum and cooled to 50 K, at which the thermoelastic damping is minimized.[6] A tunable Ti:Sapphire cw laser was used for the optical excitation in the wavelength range of λ_{ex} = 780 - 850 nm, where the band-gap wavelength of *i*-GaAs is 820 nm at 50 K.[7] This laser was focused on one of the legs of the cantilever [Fig. 1(a)], where large strain is induced by the cantilever deflection. The cantilever has the built-in potential as shown in Fig. 3(d) due to the doping effect and the surface Fermi-level pinning. Our in-plane photocurrent measurements show that the absorption-edge wavelength is ~ 840 nm, which is longer than the band-gap wavelength of *i*-GaAs. This red shift is caused by the band-tail absorption in *n*-GaAs and the electro-absorption by the built-in electric field.[7] The vibration of the cantilever was detected with a He:Ne (633 nm) cw laser via optical interferometry. This laser was focused on the near edge of the cantilever [Fig. 1(a)], where the larger displacement is obtained. The noise power density of the thermomechanical vibration was measured around the fundamental-mode frequency with a spectrum analyzer. The resonance frequency (f_0) and the quality factor (Q) measured with no excitation laser are 238,948 Hz (240,069 Hz) and 6,500 (8,500), respectively, for the [110]([-110])-oriented cantilever, where $Q = f_0/\Gamma$ and Γ the damping factor, which corresponds to the full width at half maximum of the power spectrum.

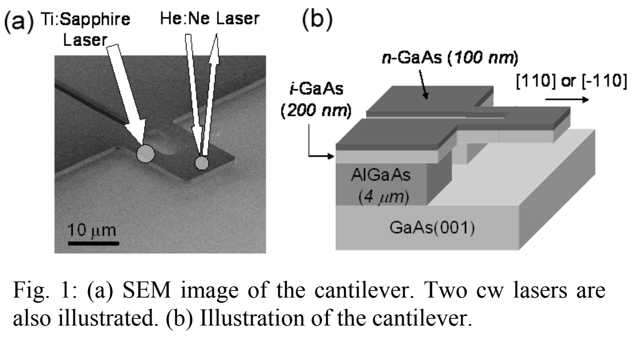

Fig. 1: (a) SEM image of the cantilever. Two cw lasers are also illustrated. (b) Illustration of the cantilever.

3. Results and Discussion

Figure 2(a) shows the noise power spectra of the thermomechanical vibration in the [110]-oriented cantilever measured for different laser power at λ_{ex} = 840 nm. With the increase in the laser power (P_{ex}), the amplitude of the noise power increases, i.e., the vibration is amplified by the irradiation of the excitation laser. When P_{ex} exceeds the critical power (~10 μW), the cantilever exhibits self-oscillations, resulting in orders of magnitude larger amplitude. In Fig. 2(b), noise power at the resonance frequency for P_{ex} = 11.2 μW is plotted as a function of λ_{ex}. The amplitude is increased when 820 nm < λ_{ex} < 850 nm and the self-oscillations appear when 835 nm < λ_{ex} < 845 nm. Increasing P_{ex} decreases the effective damping factor, Γ_{eff}, while increasing the effective spring constant, K_{eff} [Figs. 3(a) and 3(b)]. When P_{ex} reaches the critical power,

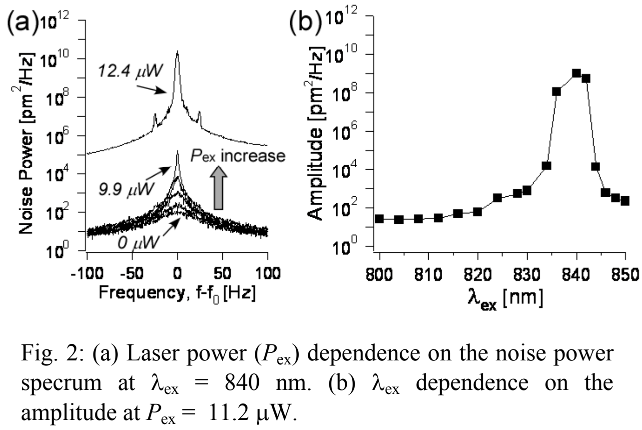

Fig. 2: (a) Laser power (P_{ex}) dependence on the noise power specrum at λ_{ex} = 840 nm. (b) λ_{ex} dependence on the amplitude at P_{ex} = 11.2 μW.

Γ_{eff} becomes zero [Fig. 3(a)]. Above this critical power, it goes into the negative damping region and the cantilever therefore exhibits self-oscillations.

The changes in Γ_{eff} and K_{eff} by laser irradiation are explained by the theory based on the damped harmonic oscillator model with photo-induced forces. Assuming that photo-induced forces act on the cantilever with a time delay τ with respect to a sudden change in the cantilever position, Γ_{eff} and K_{eff} are given by

$$\frac{\Gamma_{eff}}{\Gamma} = 1 - \frac{Q\omega_0\tau}{1+\omega^2\tau^2}\frac{K_{ph}}{K} \quad (1)$$

$$\frac{K_{eff}}{K} = 1 + \frac{1}{1+\omega^2\tau^2}\frac{K_{ph}}{K} \quad (2)$$

where K_{ph} is the force gradient given by $K_{ph} = -\partial F_{ph}(z)/\partial z\big|_{z=z(0)}$ and F_{ph} the photo-induced force.[4] Equations (1) and (2) show increasing K_{ph} increases K_{eff} while decreasing Γ_{eff}. This relation was observed in our [110]-oriented cantilever [Figs. 3(a) and 3(b)]. Equation (1) also indicates that if $Q\omega_0\tau K_{ph}/\left(1+\omega^2\tau^2\right)K > 1$, then $\Gamma_{eff} < 0$. This condition is satisfied when $P_{ex} > 10$ μW [Fig. 3(a)]. The vibration amplification is found in the [110]-oriented cantilever but not in the [-110]-oriented one. In the latter, the laser irradiation at λ_{ex} = 840 nm increases Γ_{eff} while decreasing K_{eff} [Figs. 3(a) and (b)]. This indicates the photo-induced force is related to the optically generated piezoelectric stress, as described below.

The force gradient K_{ph} originates from a change in the optical absorption by deflection-dependent strain effect via deformation potential.[7] Optical excitation with λ_{ex} ~ 840 nm causes special separation of photo-induced electrons and holes in the *n*-GaAs layer [Fig. 3(d)] and it results in the piezoelectric stress in the longitudinal direction. This stress produces a bending moment and influences the deflection of the cantilever. This situation is the same as the cantilever is subjected to photo-induced vertical forces (F_{ph}). If the [110]-oriented cantilever deflects downward, the deformation potential reduces the band gap of the *n*-GaAs layer while increasing the band gap of the *i*-GaAs layer. Thus, the optical absorption in the *n*-GaAs layer is increased, and subsequently F_{ph} is enhanced (i.e., $F_{ph} + \Delta F_{ph}$). In contrast, if the cantilever deflects upward, the band gap in the *n*-GaAs layer is widened and F_{ph} is oppositely weakened (i.e., $F_{ph} - \Delta F_{ph}$). This force gradient provides the vibration amplification of the cantilever. On the contrary, in the [-110]-oriented cantilever, the direction of F_{ph} is opposite because the sign of the piezoelectric constant is opposite between [110] and [-110] orientations ($d_{31} = -d_{32}$).[7] Therefore, the force gradient results in the vibration damping. This effect becomes prominent when the change in optical absorption by strain is enhanced, i.e., at near the absorption-edge wavelength.

Note that the optical absorption process only in the one side of the cantilever is essential to this piezoelectric backaction. If absorption occurs in both *n*- and *i*-GaAs layers (i.e., $\lambda_{ex} \leq$ 820 nm), total absorption becomes insensitive to the deflection of the cantilever, although the deflection-dependent strain effect changes the relative absorption between the two layers. Therefore, in this case, ΔF_{ph} almost disappears (i.e., $K_{ph} \cong 0$). This explains the reason why backaction is not observed for the band-gap wavelength of *i*-GaAs (λ_{ex} = 820 nm).

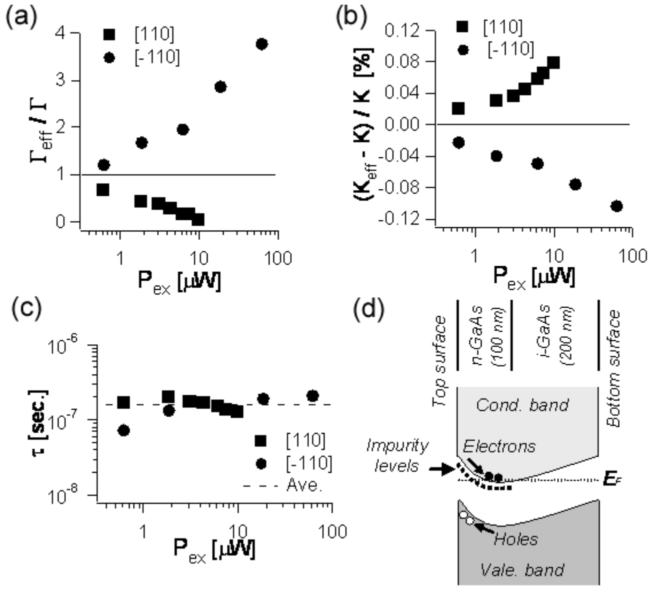

Fig. 3: Change in Γ_{eff} (a), K_{eff} (b), and τ (c) for P_{ex} in [110]- and [-110]-orineted cantilevers at λ_{ex} = 840 nm. (d) The energy band diagram. Optically excited electrons and holes move to the opposite direction due to the built-in potential.

From Eqs. (1) and (2), we can obtain the response time as $\tau = (\Gamma - \Gamma_{eff})/(\omega_{eff}^2 - \omega_0^2)$. Figure 3(c) shows the relation between τ and P_{ex} in [110]- and [-110]-oriented cantilevers measured for λ_{ex} = 840 nm. τ is almost constant with respect to the laser power and the average values are the same for both cantilevers (τ_{ave} = 160 ns). τ_{ave} is on the order of typical non-radiative recombination lifetime in GaAs,[8] indicating that the backaction is related to the spatial separation of electron-hole pairs.

4. Conclusions

We have demonstrated vibration amplification, damping, and self-oscillations in GaAs microcantilevers by carrier excitation.

Acknowledgements

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References

[1] T. J. Kippenberg and K. J. Vahala, Science **321**, 1172 (2008).
[2] O. Arcizet et al., Nature **444**, 71 (2006).
[3] A. Schliesser et al., Phys. Rev. Lett. **97**, 243905 (2006).
[4] C. Metzger and K. Karrai, Nature **432**, 1002 (2004).
[5] H. Okamoto et al., Appl. Phys. Express **2**, 035001 (2009).
[6] H. Okamoto et al., Phys. Stat. Soli (c) **5**, 2920 (2008).
[7] S. Adachi, *GaAs and Related Materials*, (World Scientific, 1994).
[8] G. B. Lush et al., Appl. Phys. Lett. **61**, 2440 (1992).