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Room-temperature photoinduced effects in elasticity and mechanical loss of GaAs for applications in high-precision optical metrology

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Abstract. Crystalline coating materials like AlGaAs/GaAs have the potential to revolutionise applications in high-precision optical metrology, such as ultra-stable laser cavities or gravitational wave interferometers. The primary driver for that is the promise of reduced noise and, thus, enhanced stability and measurement sensitivity. However, recent investigations revealed that the aspired noise level could be out of reach as an additional noise source is present, seemingly originating from intrinsic material properties and being related to the illumination of the material. To contribute to understanding this effect, we employ mechanical spectroscopy to explore the illumination-dependent mechanical loss of GaAs flexures at mechanical frequencies from 100 Hz to 94 kHz. The results indicate that photoinduced effects in bulk GaAs change the elasticity and mechanical loss with relaxation times of several minutes.

1 Introduction

Ultra-stable laser resonators for high-precision optical metrology, e.g., for gravitational wave detection [1–3] or cavity quantum electrodynamics [4–6], are severely limited by noise sources, e.g., Brownian thermal noise of the mirror coatings. To overcome this limitation, crystalline AlGaAs/GaAs coatings are a promising candidate as a low-noise material due to their low mechanical loss [7, 8]. However, it has been recently found that the predicted noise level of the optical cavity is exceeded by an unknown excess noise, which seems to be connected to photoinduced effects [9]. In investigations using mechanical spectroscopy to measure the material's mechanical loss, photo-induced effects have also been observed [10].

To better understand these effects, we studied the room-temperature mechanical loss characteristics of a GaAs flexure made of bulk material at wavelengths from 450 nm to 1700 nm. We investigated the mechanical loss characteristics for a range of mechanical resonance frequencies of 100 Hz to 94 kHz. To determine the mechanical loss factor of a given material, we analyzed the exponential decay of a mechanical oscillation at a resonance frequency f0 with the characteristic time τ. This decay provides insight into the dissipated energy, allowing for the determination of the mechanical loss factor $\phi = (\pi f_0 \tau)^{-1}$.

2 Results and Discussion

In an initial experiment in which the sample was illuminated with a flashlight showing a significant change both

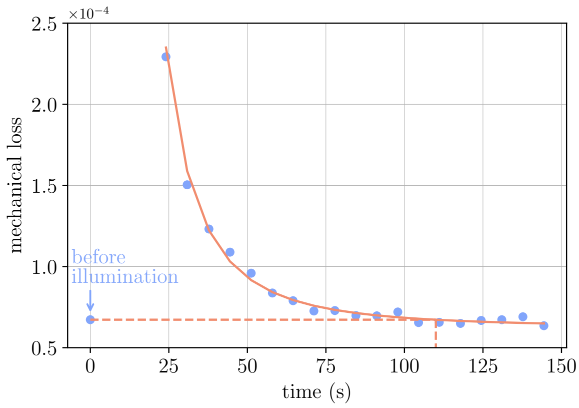

Figure 1. Photoinduced relaxation of the mechanical loss factor. After 10 seconds of illumination with a flashlight, the mechanical loss is continuously measured until it reaches the original value. A relaxation time of about 110 seconds is estimated.

in the mechanical loss factor and the resonance frequency. After switching off the illumination, it takes more than 100 seconds to return to the original state, as shown in Fig. 1.

Similar results have also been achieved using the coherent light of a laser source. To study this in detail, we performed wavelength-dependent mechanical loss measurements at room temperature. Fig. 2a exemplarily shows the results for the wavelength range around the band gap of GaAs. We kept the laser power constant at 1.5 mW to omit possible intensity-dependent effects.

From Fig. 2a, it is evident that the photon energies have a significant impact on the mechanical loss, suggesting that recombination effects influence the elastic proper-

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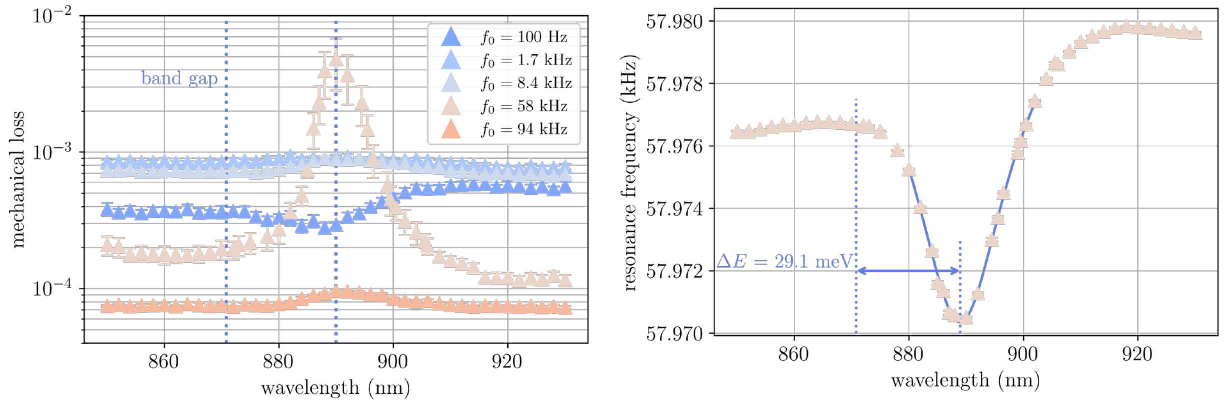

Figure 2. (a) Wavelength-dependent mechanical loss measurements of five different mechanical eigenmodes in the range from 100 Hz to 94 kHz, performed with an optical power of 1.5 mW. The strongest dependence can be seen 29 meV at 889 nm below the band gap of GaAs. (b) The same behavior is observed in the change of the resonance frequency with a minimum at 889 nm.

ties. Notably, when the excitation energy is 29 meV lower than the material's band gap, the mechanical loss exhibits a pronounced increase. Furthermore, we observe that the mechanical resonance frequency also has a wavelength dependence, as illustrated in Fig. 2b with the pronounced minimum at a wavelength of 889 nm. For wavelengths below the band gap, the resonant frequency is lower compared to its value for wavelengths above the band gap.

As the resonant frequency is directly proportional to the Young's modulus, a decrease in the resonant frequency implies a reduction in Young's modulus. The Young's modulus Y can be mathematically expressed as [11]

$$Y = \frac{1}{V_0} \times \left(\frac{\partial^2 E}{\partial \epsilon^2}\right)_{\epsilon=0}, \quad (1)$$

where V_0 represents the equilibrium volume, E the total energy, and ϵ the axial strain. Consequently, any alterations in strain within the materials lead to corresponding changes in Young's modulus, ultimately causing a reduction in the resonant frequency.

Numerous research groups have conducted Density Functional Theory (DFT) analyses to investigate the effects of electron-hole doping in silicon-based materials [11–13]. The findings of these works demonstrate that Young's modulus diminishes with the introduction of excess electrons and holes. Furthermore, an increase in free charges intensifies the reduction in Young's modulus. This effect could be similar in GaAs. Explanations for photoinduced changes in mechanical loss for GaAs can be found, for instance, in the work of Watanabe *et al.* [14]. These explanations align with our observed behavior in the mechanical loss characteristics. Induced laser light with wavelengths shorter than the band gap results in a decrease in the resonant frequency. When the excitation wavelength equals the band gap transition, the most significant impact on both mechanical loss and resonant frequency originates from efficient optical absorption. However, the observed relaxation times of several minutes indicate that a metastable state is involved whose origin still is not clear. This work is thus a first step towards a more comprehensive understanding of photoinduced effects in GaAs.

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