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One-port SAW resonator on diamond made of isotopically enriched ^{12}C

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***Abstract*— We herein investigated surface acoustic wave (SAW) filters made of diamond and demonstrated that SAW resonators of 5 GHz band can be easily realized. Diamond has been previously studied for application in power devices and quantum computers. In particular, ^{12}C diamond has been applied to quantum computers using nitrogen-vacancy (NV) centers. We fabricated a SAW resonator for ^{12}C isotopically enriched diamond. Our resonator has a resonance frequency of 6 GHz and an anti-communicating frequency of 13 GHz. In the case of the Sezawa mode, the sound speed increased by 30%. We also found that the Young's modulus doubled with the removal of a small percentage of ^{13}C. However, the reason for high coupling factor is yet to be discovered.**

Keywords—diamond, isotope ^{12}C, SAW resonator

I. INTRODUCTION

High frequency elastic wave devices utilizing surface or bulk acoustic waves (SAWs and BAWs, respectively) are widely used in fourth-generation mobile phone systems owing to their small size, steady temperature characteristics, and the quality factor, *Q,* of the resonator that controls the performance of the filter and clock source being large. As communication traffic is expected to increase by over 1000 times than that at present, millimeter waves are now being employed as carrier frequencies in fifth-generation mobile communication systems. In addition, 3–6 GHz band is also being utilized. S. Fujii et al., reported that the one-port resonator with an interdigital transducer (IDT)/AlN/single crystal diamond structure has an excellent *Q* of 8346 at 5.2 GHz [1].

Diamond has also been investigated for other applications such as in power devices and quantum computers. Diamonds made of isotopic enriched ^{12}C have been extensively studied for utilizing their nitrogen-vacancy (NV) centers in the application of quantum computers [2]. In contrast, natural carbon contains approximately 1.2% of ^{13}C in diamonds. Thermal conductivity has been reported to increase by roughly 1.5–1.8 times by removing approximately 1% of ^{13}C, resulting in a ^{12}C enriched diamond [3]. Anthony, et al. suggest that the reason for this increase in thermal conductivity is the change in the mean free path of phonons, assuming that heat transfer does not affect heat capacity and sound velocity with a high concentration of ^{12}C. Therefore, the phonon speed and SAW can be considered to be correlated. Because the wavelength is defined by the electrode width, the sound speed of SAW was investigated. We applied ^{12}C enriched diamonds to a SAW device to enhance the performance of SAW characteristics such as phase velocity.

II. EXPERMENTAL

Type Ib diamond single crystals with (100) orientations, which were synthesized by a high-pressure, high-temperature method (HPHT) at Sumitomo Electric Industries, Ltd., (Osaka, Japan), were used as SAW substrates. Homoepitaxial isotopic (^{12}C) enriched diamond was grown with a thickness of 4.0 μm on the substrate using a microwave plasma-assisted chemical vapor deposition (MPCVD) system. Teraji, et al. developed this system for high purity diamonds. The ^{12}C enrichment obtained was 99.995%. [4] In addition, Raman spectroscopy was used to evaluate the diamond for the amount of ^{12}C present.

We fabricated a one-port SAW resonator with an interdigital transducer (IDT)/AlN/homoepitaxial isotopically (^{12}C) enriched diamond. The AlN thin film as a piezoelectric material was deposited with a thickness of 0.7 μm on the film using an RF magnetron sputtering machine (Annealva, Japan) and electron cyclotron resonance (ECR) sputtering machine (JSW afty, Japan). Subsequently, electron beam lithography, metal deposition, and a lift-off process were applied to fabricate the IDT pattern with a wavelength of 2.0 μm and an electrode width of 0.5 µm. From the FEM calculations, the value of film thickness (*H*)/ wavelength(λ) was found to be 0.35, and a Sezawa (2nd mode) mode wave with a phase velocity, *Vp* of 11000 m/s and a coupling factor, K^2 of 1.2, was excited, as shown in Fig. 1 and Fig. 2 [1]. Fig. 3 shows the details of the proposed design.

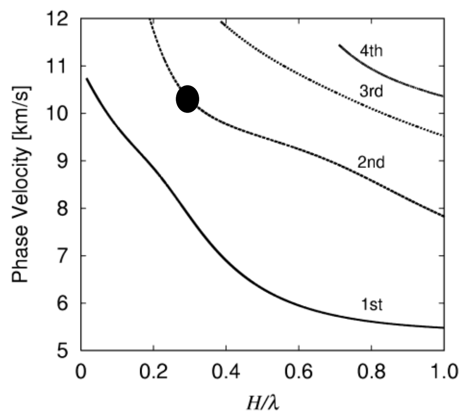


Fig. 1. Phase velocities (V_P) as a function of normalized AlN thickness (H/λ) for different SAW modes; the black circle marks the selected thickness

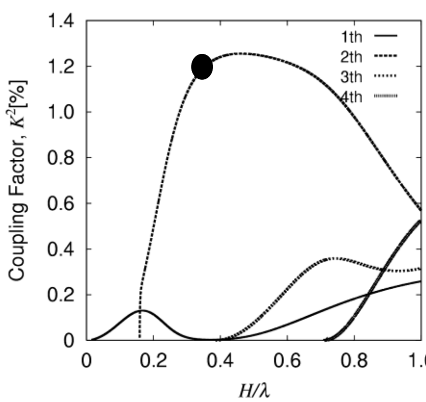


Fig. 2. Electromechanical coupling coefficient ($K^{2)}$ as a function of normalized AlN thickness (H/λ) for different SAW modes; the black circle denotes the selected thickness

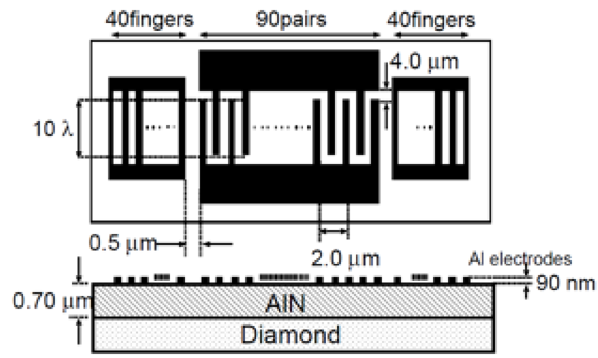


Fig. 3. Structure and IDT design of the one-port SAW resonator used in this study.

III. Results and Discussion

Fig. 4 depicts the Raman spectra of the 4 µm thick ^{12}C diamond and the natural diamond type Ib. The enriched ^{12}C diamond peak is slightly lower than that of the natural diamond which is 1332.4 cm^{-1} [5].

Fig. 5 depicts the results of the absolute impedance of the best performing one-port SAW resonator, using a network analyzer. Table I lists the extract parameters of the SAW resonators from Fig. 1. After being excited by the 2nd mode SAW, the resonance and anti-resonance frequencies were f_r = 6.77 GHz and f_a=13.65 GHz, respectively. The phase velocity obtained from the resonance frequency was 13533 m/s. A phase velocity of 10500 m/s was derived based on an FEM calculation of the AlN/diamond structure. The phase velocity of the ^{12}C enriched diamond SAW was 30% greater than that of the natural abundance diamond.

In other words, the Young's modulus of the ^{12}C enriched diamond was almost double that of the natural abundance diamond.

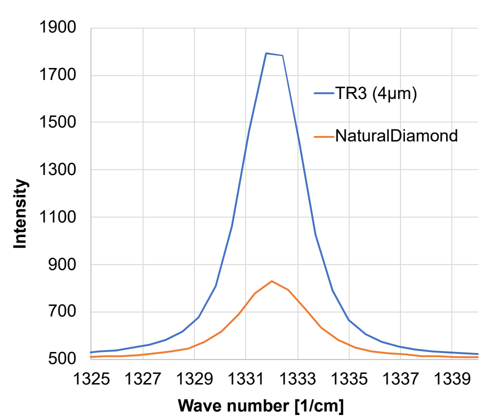
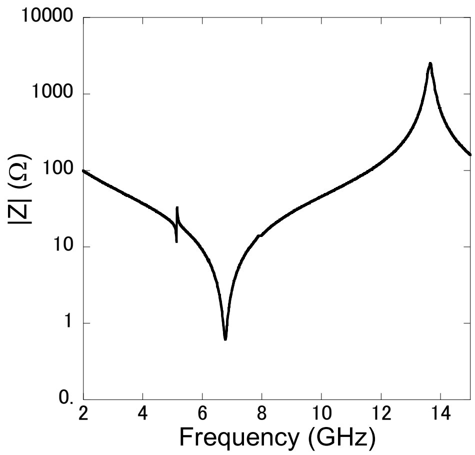
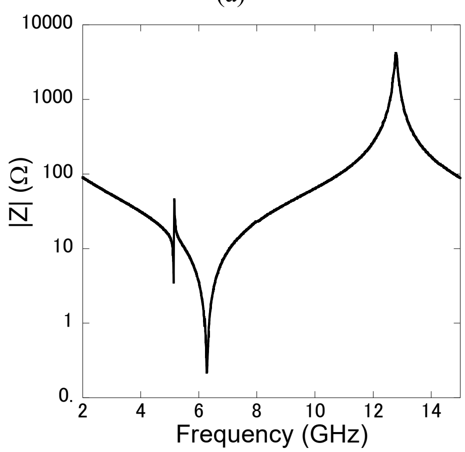


Fig. 4. Raman spectra of the diamond made of 4 µm thick ^{12}C and the natural diamond type Ib.



(a)



(b)

Fig. 5 Measurement results of the one-port diamond SAW resonator for the ^{12}C isotopically enriched diamond. (a) AlN deposited by RF-magnetron sputtering, (b) AlN deposited by ECR sputtering.

TABLE I. MEASUREMENT SUMMARY

	Resonator parameters		
	Resonance freq. (Hz)	***Phase velocity (m/s)***	***K^2 (%)***
FEM	5.25	10500	1.2
RF sup.	6.76	13533	60
ECR	6.77	13544	60

The coupling factor is extracted from Fig 5 using the equation (1):

$$K^2 = \left(\frac{\pi}{2}\right)\left(\frac{f_r}{f_a}\right)\left(\frac{f_a-f_r}{f_a}\right) \quad (1)$$

From Table I, it can be observed that the coupling factors of the isotopic enriched diamond are larger than that of the natural abundance diamond. However, explaining this phenomenon at this point is still a challenge. The aforementioned results demonstrate the improved performance of the SAW resonator using the ^{12}C enriched diamond.

IV. CONCLUSION

We fabricated a novel one-port diamond SAW resonator for ^{12}C isotopically enriched diamonds. The resonator has a resonance frequency of 6 GHz and an anti-communicating frequency of 13 GHz. In the Sezawa mode, the sound speed increased by 30%. The Young's modulus doubled with the removal of a small percentage of ^{13}C. However, the explanation for high coupling factor could not be derived.

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