Fabrication of AlN HBAR Devices for Spin Manipulation of Diamond NV Centers

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Principal Investigator(s): Gregory Fuchs[1]

User(s): Johnathan Kuan[2], Huiyao Chen[3]

Affiliation(s): 1. Applied and Engineering Physics, 2. Department of Physics, 3. Department of Physics; Cornell University

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Contact: gdf9@cornell.edu, jk2788@cornell.edu, hc846@cornell.edu

Website: http://fuchs.research.engineering.cornell.edu

Primary CNF Tools Used: AJA sputter, OEM Endeavor M1, GCA 5X stepper, Westbond 7400A ultrasonic wire bonder

Abstract:

Previous work with nitrogen-vacancy (NV) centers in diamond have demonstrated coupling between the NV spins and strain. Harmonic strain can be introduced into diamond lattice with transducers such as high-overtone bulk acoustic resonators (HBAR), which introduce a stress wave into the diamond. This strain can be used to coherently control the NV center spins. We describe our current work in fabricating HBAR devices using aluminum nitride (AlN) as the piezoelectric and characterize the performance of our device, which uses a 2 µm film of AlN. With our AlN HBAR device, we find resonance modes from 300 MHz to 3.5 GHz with quality factors ranging from 800 to 1700.

Summary of Research:

The diamond NV-center consists of vacancy in the diamond lattice that is adjacent to a substitutional nitrogen. The goal of our research is the manipulation of the spin states of NV center through strain. Strain is introduced into the diamond lattice with piezoelectric transducers, such as high-overtone bulk acoustic resonators (HBAR). Examples of previous work with HBAR devices and diamond include coupling of the NV center spins with strain [1], coherent control over magnetically forbidden transitions of NV centers [2], continuous dynamical decoupling [3], and cooling of a mechanical resonator with a high-density NV ensemble [4].

In our current work at CNF, we are working on process development of HBARs that use AlN as the piezoelectric film with the aim of applying these resonators for control of NV spins for quantum metrology applications such as angle sensing [5]. Previously, we would have to have to AlN film deposited externally from CNF, but with the recent addition of the OEM Endeavor M1 tool, we are able to do the entire fabrication in-house.

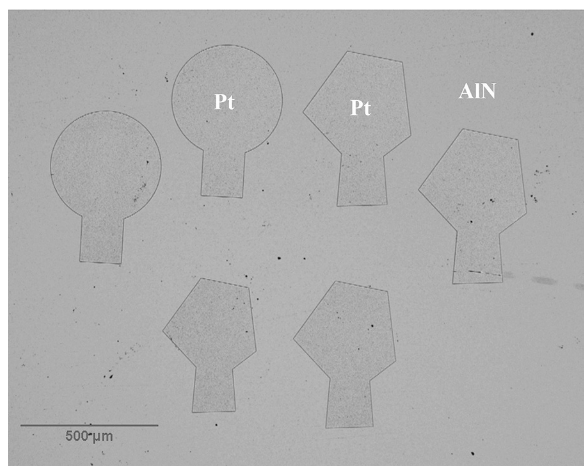

Figure 1: Final HBAR devices on the optical-grade diamond substrate. The devices are approximately 500 µm large. The top electrode, which defines the HBAR, consists of a Ti/Pt film and made through lift-off. These electrodes sit on the AlN layer which is 2 µm thick.

We fabricate these HBAR devices using AlN as the piezoelectric layer through the following process. The substrate that we work with is a 3 mm by 3 mm diamond piece. On top of the substrate, we sputter a layer of Ti/Pt (103 nm total thickness) to act as the bottom electrode of the device using the AJA sputter deposition tool at CNF. Following this, we sputter the piezoelectric layer of AlN (2 µm) using the OEM Endeavor M1 tool. To finish the fabrication, we define the shape of the top electrode though photolithography with the 5X stepper and sputter a Ti/Pt film (10nm/180nm) again with the AJA sputter deposition. The excess metal film on the top layer is

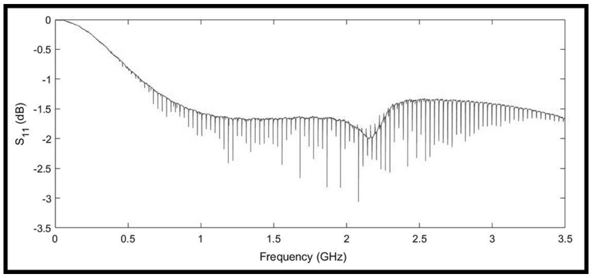

Figure 2: S11 measurement of the AlN HBAR device fabricated on optical-grade diamond. HBAR resonances modes are present in the S11 measurement in a frequency range of approximately 500 MHz to 3.5 GHz.

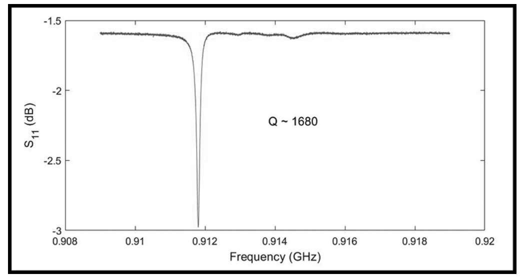

Figure 3: VNA Measurement single resonance mode of AlN HBAR device fabricated on optical-grade diamond. The quality factor that is extracted from fitting to Q-circle model is approximately 1680.

removed through lift-off, leaving behind the top electrode on the piezoelectric layer. In Figure 1, we see the final HBAR devices that are fabricated on diamond. These devices are approximately 500 µm large.

We tested the electromechanical response of our HBAR device with a vector network analyzer. The devices presented here are fabricated on optical-grade diamond, with a thickness of 287 µm and a variation of approximately 1 µm across 3 mm. Minimizing the thickness variation of the substrate is important for these devices as the top and bottom surfaces of the substrate act as planar mirrors for the stress wave injected into the substrate by the HBAR. The planar surfaces allow for an acoustic standing wave in the substrate. Having a large thickness variation is detrimental to the quality factor of our resonator. Using the vector network analyzer, we looked at the S11 response of our HBAR device. When the HBAR is resonant with the applied power, less power is reflected, which is seen as a dip in the S11 measurement. As seen in Figure 2, from the S11 measurement, we find that the resonance modes of our device span from 500 MHz to 3.5 GHz, with quality factors in the range of 800 to 1700. In Figure 3, we see a resonance mode with a quality factor of 1680 which was extracted using the Q-circle method [6].

Further work in being done to improve the performance and the consistency of these devices and to optimize the fabrication process. For example, the quality of the AlN piezoelectric layer limits the quality of the device. In our current process, we use a TMAH developer to define the top electrode area. However, TMAH etches the surface of the AlN film, increasing the surface roughness of the film, which lowers the performance of the device.

References:

[1] E. R. MacQuarrie, T. A. Gosavi, N. R. Jungwirth, S. A. Bhave, and G. D. Fuchs, Mechanical spin control of nitrogen-vacancy centers in diamond, Phys. Rev. Lett. 111, 227602 (2013).

[2] E. R. MacQuarrie, T. A. Gosavi, A. M. Moehle, N. R. Jungwirth, S. A. Bhave, and G. D. Fuchs, Coherent control of a nitrogen-vacancy center spin ensemble with a diamond mechanical resonator, Optica 2, 233 (2015).

[3] E. R. MacQuarrie, T. A. Gosavi, S. A. Bhave, and G. D. Fuchs, Continuous dynamical decoupling of a single diamond nitrogen-vacancy center spin with a mechanical resonator, Phys. Rev. B 92, 224419 (2015).

[4] E.R. MacQuarrie, M. Otten, S.K. Gray, and G.D. Fuchs, Cooling a mechanical resonator with nitrogen-vacancy centres using a room temperature excited state spin-strain interaction Nature Communications 8, 14358 (2017).

[5] Ashok Ajoy and Paola Cappellaro. Stable three-axis nuclear gyroscope in diamond, Phys. Rev. A 86, 062104 (2012).

[6] D. A. Feld, R. Parker, R. Ruby, P. Bradley, and S. Dong, in IEEE International Ultrasonics Symposium (IUS), Beijing, 2008 (IEEE, Piscataway, NJ, 2008), p. 431.