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Suspended Waveguide for Mechanical Driving of Color Centers in Diamond

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Abstract: We demonstrate the transmission of a ∼4-GHz surface acoustic wave across a suspended diamond waveguide. This enables simultaneous coherent mechanical driving of, and optical access to, diamond-based color centers. © 2022 The Author(s)

1. Introduction

Atomic defects in solids, including silicon vacancy centers (SiVs) in diamond, are appealing for quantum memory because of their long spin coherence times (yielding long storage times) and good optical properties (to either read out, or interface an optical photon, with the memory) at cryogenic temperatures. To extend storage times, coherent control of the spin is required, e.g. to implement dynamical decoupling, which is usually achieved by applying microwave pulses. However, such pulses unavoidably induce deleterious heating due to interactions with the solid. This effect can potentially be minimized for an SiV spin: by leveraging its strong, and unique, strain susceptibility property, it can be driven by mechanical waves [1,2]. Consequently, surface acoustic waves (SAWs) have been utilized to coherently drive SiV spins in bulk diamond, and with orders-of-magnitude lower power than what is required using microwave pulses [2]. However bulk diamond restricts photon collection efficiencies due to total internal reflection and does not allow high mechanical mode confinement, which hinders driving rates. In addition, a decreased mechanical mode volume (or cross-section) could allow reaching the limit of controlling SiV spins with single phonons. Here, we present a suspended diamond waveguide that provides both improved optical access and mechanical interaction of SiVs compared to bulk diamond.

2. Device Design and Fabrication

Our waveguide supports both photonic and SAW modes, at 737 nm and ∼4 GHz, respectively, and tapers to a bulk region where SAWs are generated by interdigital tranducers (IDTs). (Fig. 1(a)). Two sets of IDTs are used to characterize the transmission of SAWs through the waveguide. Although similar waveguide geometries have been demonstrated in other materials [3], these do not host the excellent and well-understood quantum defects offered by diamond.

To fabricate the waveguide and IDTs, a 700-nm-thick layer of AlN is sputtered onto diamond as the piezeoelectric material to transduce microwave signals. Next, 100 nm of Cr/Au is deposited on top to form two sets of intermeshed (50% duty cycle) electrodes for the IDTs. The tapered coupler and the waveguide are etched through the AlN and into the diamond. The waveguide region is then suspended by a quasi-isotropic etch using oxygen plasma.

Application of a 4.2 GHz microwave signal to the IDT excites a Rayleigh SAW mode with a wavelength of 2 μm. This mode has significant overlap with the suspended waveguide modes at the same frequency, allowing the tapered structure to adiabatically transfer one to the other, as shown in 1b. The waveguide and SAW modes, and the band structure are simulated using finite element method.

The waveguide is designed for transmission of 737 nm light to match the resonance frequency of an SiV. Because diamond has a higher refractive index than AlN, the lowest-order optical mode will be confined inside the diamond waveguide, strongly overlapping with emission from an embedded SiV.

3. Characterization

A vector network analyzer is used to measure transmission between, and reflections from, the IDTs, as shown in fig 1c. At 4.18 GHz, we measured the S-parameters for reflection S_{11} of -1.8 dB and transmission S_{21} of -50 dB. The bandwidth is 10 MHz, roughly determined by the IDT resonance frequency and the total number of electrode pairs. The intensity reduction in the reflection spectrum S_{11} indicates that the microwave power is transduced into SAW, and the transmission peak in S_{21} indicates that the mechanical wave propagates across the

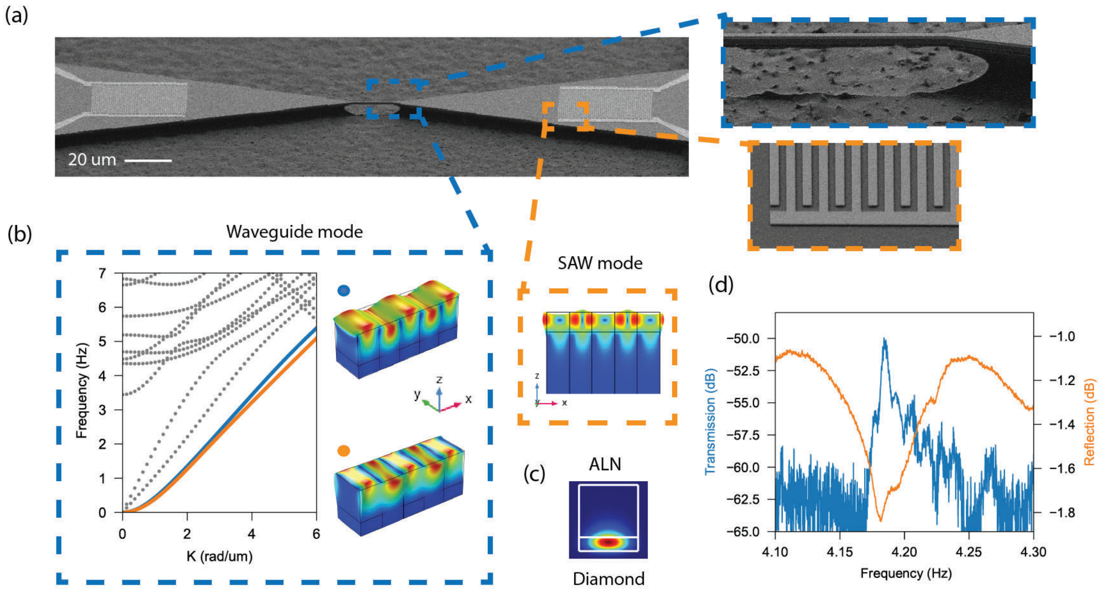

Fig. 1. a) Scanning electron microscope images of the fabricated waveguide, tapered regions, and associated IDTs. The electrode thickness is 100 nm and the period is 2 μm. The waveguide is 785 nm wide and has a 700-nm-thick layer of AlN on top of 200 nm of diamond. Devices with lengths ranging from 5 to 20 μm all showed at least -70 dB of transmission. The insets show the detail of the IDT and the taper connected to the suspended waveguide. b) Mechanical simulation results of the device. The color shows total displacement. c) Optical simulation of the waveguide. The color corresponds to normalized electric field intensity, and the field is confined mostly in diamond. d) Measured transmission and reflection of the device.

suspended waveguide. We believe that more precisely-controlled etching processes will reduce fabrication defects and improve transmission in future iterations of the devices.

4. Outlook

For future experiments with SiVs, one end of the suspended waveguide will be replaced by a taper, and a fiber will be touched down on the waveguide to provide low-loss optical coupling between the suspended diamond waveguide and an optical fiber.

In our previous work [2], SiVs were driven at a maximum Rabi rate of 50 MHz. With more than an order of magnitude smaller mode area of our structure, we expect to achieve further enhanced Rabi rates by a factor of 5 as it scales linearly with spin-phonon coupling rate of the waveguide, which scales as the inverse of squareroot of mode area. . This structure also opens the door to local control of color centers in suspended phononic crystals [4] and to color-center waveguide quantum electrodynamics that require a high frequency phonon source [5].

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