NANO-GAP PIEZOELECTRIC RESONATORS FOR MECHANICAL RF MAGNETIC FIELD MODULATION

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ABSTRACT (104 WORDS – MAX 150)

Novel piezoelectric MEMS resonators with magnetic shielding have been developed to mechanically generate RF magnetic fields in the MHz frequency range from static magnetic fields. Thermally evaporated thin film nickel iron (NiFe) (10 to 20 nm) was deposited with a saturation flux density of 0.5 T, coercivity of 500 A/m and a high relative permeability of 3.7 x 10³. Aluminum nitride (AlN) resonators developed for high frequency operation, resonate in a contour mode to increase and decrease a gap surrounding the resonator. This gap, 200 to 350 nm, is formed using a silicon sidewall deposition as a sacrificial spacer. Resonators with frequencies up to 60 MHz have been fabricated and tested.

KEYWORDS
Piezoelectric, resonator, magnetic field, RF, MEMS, NiFe, permalloy, inductor, flux switch.

INTRODUCTION

MEMS technology is making profound changes in RF magnetic field generation but in a shift from shrinking conventional components into 3-D and planar coil structures [1], [2], this paper presents using a soft magnetic, high permeability alloy to interact with a static magnetic field. Nano-gap piezoelectric MEMS resonators, shown in Figure 1, have been developed in conjunction with the soft magnetic, high permeability alloy to create localized regions of a RF magnetic field.

A gap in a material with a high magnetic permeability causes magnetic field lines to leak into the surrounding ambient environment (air). If this gap is increased or decreased, the density of the field at a given point in that area will change. MEMS fabrication techniques enable the design and fabrication of a device that can take advantage of this behavior and locally modulate a static magnetic field.

Piezoelectric actuation was chosen to decrease the effect of mass loading by the magnetic shielding alloy while achieving high frequency operation. By using bulk mode actuation, the surface area of the device could be maximized for deposition of the magnetic shield. Aluminum nitride (AlN), a piezoelectric material with a high sound velocity of ~10 km/s which enables the design of resonators with resonance frequencies in the MHz and GHz range, was selected to actuate the closing and opening of the gaps. A z-oriented AlN film with in-plane symmetry...
(piezoelectric coefficient $d_{31} = d_{21}$) and contour mode resonators with resonance frequencies in the MHz range were developed by Piazza et al [3]. Leveraging this technology, the fabrication process was modified to create sub-micron gaps around the perimeter of the AlN resonators using a sidewall deposition material as a spacer and backfilling the etched AlN. After the removal of the sacrificial spacer material, the devices are covered with the thin film magnetic shield alloy, NiFe. Future operation of the device will be obtained by placing a magnet beneath the die to provide a static magnetic field. The magnetic field in the ambient environment above the resonator will vary locally with the frequency of the resonator.

**MAGNETIC SHIELDING**

To maintain the high frequency operation and create a RF magnetic field, the mass of the magnetic shielding alloy needed to be minimized while maximizing the permeability and saturation flux density. This ensures the magnetic field lines are properly channeled into the material and allows for a larger range of applied static magnetic fields. This behavior can be seen in Figure 2

\[
\mu_r \text{(Air)} = 1 \\
\mu_r \text{(80Ni/20Fe)} = \text{up to } 1 \times 10^5
\]

**Figure 2: Gap in High Permeable Material in Static Magnetic Field**

NiFe is a common material in magnetic MEMS applications and the 80/20 stoichiometry, also known as permalloy, is well known material for magnetic shielding [4] because of its high relative permeability. In addition, the magnetostriction effects are reduced at this stoichiometry [5], which reduces the effect of the resonating structure on the magnetic properties of the film. While the saturation flux density is not at a maximum at this stoichiometry [6], losses in permeability at other Ni-Fe ratios would outweigh any gains in saturation flux density.

Based on dynamic analysis of the resonating structure and density of 80/20 NiFe, a target thickness of 10nm was chosen. Thermal evaporation was chosen to deposit the thin NiFe film and similar melting temperatures for the nickel (1455 °C) and iron (1538 °C) helped maintain the stoichiometric relationship between the source material and deposited thin film. Analysis of the film's magnetic properties was performed using a superconducting quantum interference device (SQUID) and a vibrating sample magnetometer (VSM). The film’s composition was verified using energy dispersive x-ray spectroscopy (EDX) and Auger electron spectrometry. The film’s magnetization was performed using a superconducting quantum interference device (SQUID) and a vibrating sample magnetometer (VSM). Analysis of the film’s magnetic properties was performed using a superconducting quantum interference device (SQUID) and a vibrating sample magnetometer (VSM). The film’s composition was verified using energy dispersive x-ray spectroscopy (EDX) and Auger electron spectrometry. The thermally evaporated NiFe films, ranging in thickness from 10 to 20 nm, have a saturation flux density of 0.5 T. This value is half of that reported in bulk [6] and allows for a large range of fields to be applied. A coercivity of 500 A/m and a high relative permeability of $3.7 \times 10^3$ were obtained which ensure the magnetic field lines will be contained within the plane of the NiFe film.

**Figure 3: Magnetic Properties of Thermally Evaporated 10 nm NiFe Film**

<table>
<thead>
<tr>
<th>Slope</th>
<th>Saturation flux density $\sim 0.5$ T ($\sim 1$ T in bulk)</th>
</tr>
</thead>
</table>

Important to limit stray magnetic fields

**Figure 4: TEM of NiFe Film on Silicon Wafer with Native Oxide**

Epoxy

NiFe

SiO$_2$

Si Wafer

9 nm
Transmission electron microscopy (TEM) analysis was done to verify the thickness of the thermally evaporated films first measured with a profilometer since these thicknesses are at the lower end of its resolution capabilities. Figure 4 shows a TEM image of the NiFe film on top of a silicon wafer with a native oxide. The thickness of the NiFe film is about 9nm. This value was important to correct for volume magnetic moment measurements performed by SQUID and VSM.

NANO-GAP FABRICATION

The aluminum nitride resonators developed by Piazza et al [3] for high frequency operation, resonate in a length extension contour mode. Taking advantage of this operation mode, nanogaps have been formed around the perimeter of the resonator using a silicon sidewall deposition as a sacrificial spacer. The in-plane resonance increases and decreases this gap.

The nano-gap piezoelectric resonators are fabricated in the following manner (outlined in Figure 5). Low stress nitride is deposited using a LPCVD furnace to act as an isolation later between the devices on the wafer. The bottom electrode is formed using a liftoff process for sputtered platinum (Figure 5a). The aluminum nitride is then sputter deposited to obtain films with stress levels ± 100 MPa. Low temperature oxide (LTO) is used to mask the ALN during a chlorine based plasma etch (Figure 5b). After the ALN etch, a thin layer of silicon that will be used for the sidewall sacrificial spacer is deposited in a LPCVD furnace (Figure 5c). Deposition temperatures from 500 to 615 C were used to deposit both amorphous silicon and polysilicon and it was found that maintaining a lower process temperature was best for the underlying platinum electrodes. Film thickness ranged from 200 nm to 350 nm with the final gap depending on the conformity of the deposition along the side walls. The space surrounding the etched ALN is then filled in using a low temperature oxide deposition. The thickness of the LTO film must be equal or greater than the step height created from the etching of the AlN and LSN films. Next the wafers are polished with a KOH based slurry designed to polish silicon dioxide (chemical mechanical polishing, CMP) This step exposes the ALN device layer as well as the silicon spacer that will be removed with the wafer is released (Figure 5d).

The top electrode is composed of sputtered Al and which is deposited and patterned after the CMP (Figure 5e). Next, openings to the bottom electrode are created using a hot phosphoric acid etch (not shown in Figure 5). The wafer is then diced to prepare for the release process and final deposition of the NiFe film. The device is release using a xenon difluoride etch that attacks the silicon sidewall spacer as well as the silicon wafer to free the space below the resonator (Figure 5f). The gases used in the etch gain access to the wafer via the sidewall spacers and require extended etch times.

The magnetic shielding alloy is incorporated without any additional lithographic steps and is deposited on the released structures after the dry release (Figure 5g). This fabrication step is integral to obtaining the sub-micron gap in the magnetic shielding film. Electrical isolation of each device is created by a trench etched in the AlN around each device during the etch to gain access to the bottom platinum electrodes (Figure 6).

![Figure 5: Outline of Fabrication Process (not to scale)](image)

- a) Deposition of LSN and Pt (Lift Off)
- b) Deposition and Etch of AlN and LSN
- c) Deposition of Silicon
- d) Deposition of SiO2 and CMP
- e) Deposition and Etch of Al
- f) Release in XeF2 etch
- g) Deposition of 80Ni/20Fe

Figure 6: Optical Micrograph of Released Nano-gap AlN Piezoelectric Resonator

![Figure 7: Nano-gap Between AlN and SiO2](image)
In Figure 6, the released area surrounding the rectangular resonator can be seen. The edges of the oxide filler that are not next to the resonator have been covered with a thin line of aluminum, thus blocking the exposure of the silicon spacer to the XeF₂ gas. The result is a filler piece firmly anchored to the LSN-Si substrate with minimal deflection. This provides a coherent plane upon which to deposit the NiFe film. The final gap after release can be seen in Figure 7.

**ELECTRIC CHARACTERIZATION**

Resonators with frequencies up to 60 MHz have been fabricated and tested and quality factors up to 700 have been experimentally determined for the resonator before the NiFe is deposited. There are slight variations in the resonance frequencies device to device due to uneven polishing in the CMP fabrication process step. This variation is not detrimental to the operation of the device because unlike FBARS, the resonance frequency of the device is not solely dependent on the thickness of the film. This is an advantage of the contour mode resonators, as described by Piazza et al [3].

The contour mode resonators were designed to have quarter wavelength (the length of the rectangular resonator for length extension mode) supports to reduce losses to the substrate. Thermally evaporating the NiFe over the entire surface was found to decrease the resonance frequency by about 2 MHz and reduce the quality factor by half. Figure 8 shows a picture of the resonance peak and the corresponding resonance frequency and Q for a contour mode resonator with a length of 80 micrometers and 10nm of NiFe deposited (f = 57 MHz, Q ≈ 300). The reduction in frequency is due to the added mass and the different stiffness coefficient of the NiFe film which reduces the wave speed of the device. The wave speed, a material property, and is proportional to the natural resonance frequency of the device.

**CONCLUSION**

Using sidewall deposition techniques and building upon the foundation of high frequency contour mode piezoelectric AlN resonators designed by Piazza et al [3], nano-gap (200 nm) piezoelectric resonators for RF magnetic field modulation have been fabricated. A process for thin film, 10 nm, 80Ni20Fe was developed according to the high frequency and magnetic modeling design requirements.

The thin film NiFe has a high saturation flux density (0.5 T), half of the bulk value, a low coercive field (500 A/m) and a permeability three orders of magnitude greater than air (3.7 x 10⁸). Retention of at least half of the bulk magnetic properties reported for 80Ni/20Fe is a profound development for the success of this research and allows for a large range of static magnetic fields to be applied and for the film to properly shield the space above the resonators. The NiFe film has been incorporated with the AlN resonators with frequencies up to 60 MHz have been fabricated and tested.

An important step in the fundamental development of mechanical generation of RF magnetic fields, this work represents a novel fabrication process, the development of thin film NiFe for magnetic shielding and the electrical evaluation of the resonators. Future research will include the static and dynamic measurement of the magnetic field surrounding the resonators.

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**REFERENCES**


