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HIGH-*Q* MICROMECHANICAL RESONATORS IN CH_4-REACTANT-OPTIMIZED HIGH ACOUSTIC VELOCITY CVD POLYDIAMOND

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ABSTRACT

Vibrating micromechanical resonators with *Q*'s greater than 30,000 have been demonstrated in CVD polydiamond material with an acoustic velocity of 14,252 m/s—the highest to date among surface-micromachinable materials for micromechanical resonators—achieved via exhaustive modifications to a CVD polydiamond deposition recipe that identify low CH_4 reactant concentration as the key to attaining high acoustic velocity. As a result of these modifications, folded-beam comb-transduced micromechanical resonators made in CVD polydiamond have now been measured with resonance frequencies 1.77X higher than that of identical polysilicon counterparts, 1.20X higher than achievable by SiC (another high acoustic velocity material contender [1]), and 1.53X higher than a previous attempt at using CVD polydiamond as a resonator structural material [2].

Keywords: wireless communications, RF MEMS, diamond, resonator

I. INTRODUCTION

Spurred by increasing interest in RF communication applications of MEMS technology [3], the frequencies of vibrating micromechanical resonators have seen dramatic increases in recent years, through which frequencies in the hundreds of MHz have now been demonstrated [4][5]. Among strategies for further extending frequencies past 1 GHz, the use of alternative structural materials with higher acoustic velocities than polysilicon, such as silicon carbide [1][4], have been particularly successful. Of the presently available set of thin-film-depositable materials, diamond potentially offers the largest acoustic velocity, with *single crystal* values on the order of 18,076 m/s [6], which is 2.24X higher than that of polysilicon and 1.50X higher than that of silicon carbide. Unfortunately, however, recent attempts to use CVD *polydiamond* as the structural material for micromechanical resonators have thus far yielded an acoustic velocity on the order of only 9,320 m/s, far lower than potentially achievable [2].

This paper reports for the first time micromechanical resonators in CVD polydiamond material with an acoustic velocity of 14,252 m/s, achieved via exhaustive changes made to the CVD polydiamond deposition recipe that identify low CH_4 reactant concentration as the key to high acoustic velocity. As a result of these changes, folded-beam comb-transduced micromechanical resonators made in CVD polydiamond are now demonstrated with resonance frequencies 1.77X higher than that of identical polysilicon counterparts, and with similar *Q*'s.

II. CVD POLYDIAMOND RECIPE VARIATIONS

The fabrication process that achieves CVD polydiamond devices with the final cross-section of Fig. 1 is similar to that of [2], except that doped LPCVD polysilicon (rather than metal) is used as the interconnect layer, and a 920°C LPCVD oxide (HTO) is utilized as the sacrificial layer (rather than PECVD oxide). These adjustments were made mainly to allow a wider variance in diamond deposition and etch recipes during the search for the right recipe.

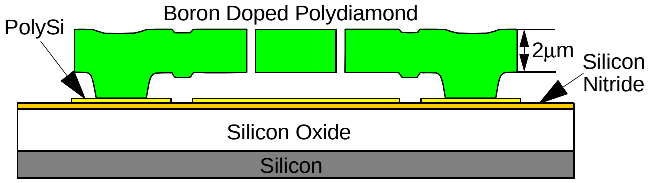

Fig. 1: Final cross-section of a CVD polydiamond micromechanical device in the process technology used for this work.

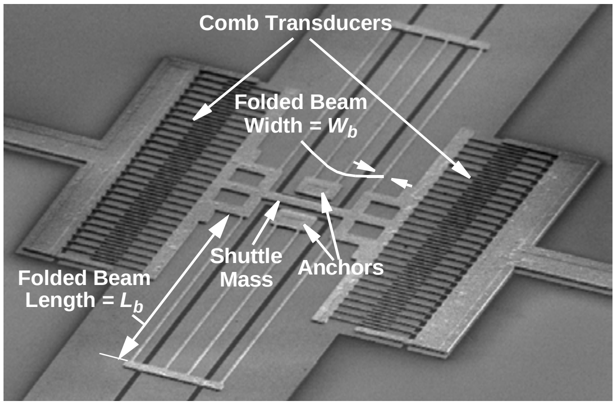

Fig. 2: SEM of a fabricated TypeD folded-beam, comb-transduced CVD polydiamond micromechanical resonator.

As in [2], CVD polydiamond was deposited by first establishing a seed layer of diamond with a sufficient nucleation density, then depositing and *in situ* boron doping the diamond material via a microwave PECVD process, still using 2.45 GHz microwaves, but this time changing the substrate temperature and the concentrations of the CH_4 and B_2H_6 reactants, in search of an optimum recipe that yields high acoustic velocity while retaining high-*Q*, low stress, and low surface roughness. Table I presents a listing of four representative recipe variations.

III. EXPERIMENTAL RESULTS

Figure 2 presents the wide-view SEM of a fabricated TypeD (c.f., Table I) CVD polydiamond folded-beam micromechanical resonator. Figures 3 and 4 present measured frequency characteristics using the inset circuits under 50μTorr vacuum for a TypeC and a TypeD device, both with identical dimensions, but showing widely disparate resonance frequencies of 19.893 kHz and 27.345 kHz, respectively. As summarized in Table I, and assuming a constant density of 3,500 kg/m^3 for CVD polydiamond deposited with CH_4 concentrations less than 1% [9], these frequencies correspond to acoustic velocities of 10,419 m/s and 14,252 m/s, with the TypeD material showing a 1.37X higher acoustic velocity than the TypeC. The TypeD device also exhibits a much higher *Q* of 36,460 than the 19,892 of the TypeC.

From Table I the main difference between these two devices is in the CH_4 concentrations used during CVD diamond deposition, which was much smaller (0.33%) for the higher frequency TypeD device than for the TypeC device (0.9%). This, together with the observation that lower deposition rates attained with low CH_4 reactant concentrations lead to smaller deposits of non-diamond carbon

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Table I: CVD Polydiamond Properties vs. Deposition Conditions

Parameter	TypeA*	TypeB†	TypeC‡	TypeD‡	Units
Pretreatment? [2]	no	yes	yes	yes	yes/no
Temperature	575	750	750	800	^oC
CH_4 Concentration	0.33	0.33	0.9	0.33	%
Power	800	800	600	800	W
B_2H_6 Concentration	6.7	6.7	6.7	11.1	10^{-5}%
H_2 Flow Rate	900	900	900	900	sccm
Deposition Time	2,400	1,200	480	1,200	min
Thickness	1.4	2.11	1.86	2.56	µm
Surface Roughness	145	80	60	50	nm
Resonance Frequency, f_o	2938	35.82	19.893	27.352	kHz
Quality Factor, Q	6,225	19,500	19,892	36,460	—
Young's Modulus, E	305	654	380	711	GPa
Density, ρ [9]	3,500	3,500	3,500	3,500	kg/m^3
Acoust. Vel. (= $\sqrt{E/\rho}$)	9,320	13,670	10,419	14,252	m/s

* Clamped-clamped beam resonator with length L_r=55µm, width W_r=8µm, thickness h_r=1.1µm.

† Folded-beam, comb-transduced resonator with L_b=160µm, W_b=2µm, shuttle mass $m_s=9.03\times10^{-11}$kg.

‡ Folded-beam resonator with the design of Figs. 3 and 4.

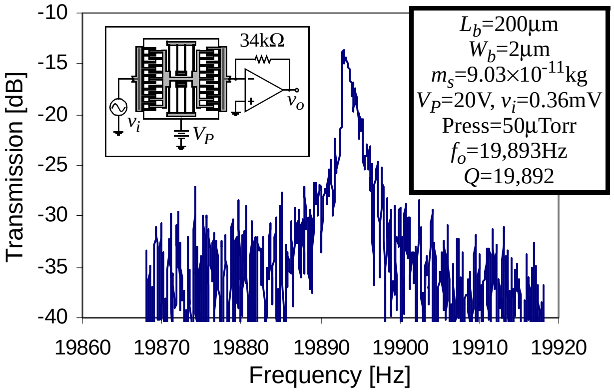

Fig. 3: Measured frequency characteristic (under 50 µTorr vacuum) for the TypeC polydiamond folded-beam resonator.

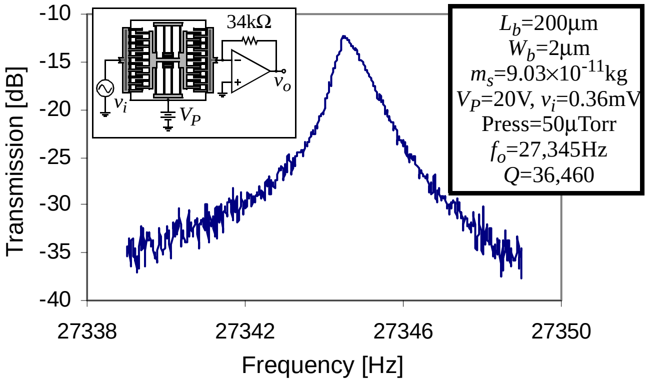

Fig. 4: Measured frequency characteristic (under 50 µTorr vacuum) for the TypeD polydiamond folded beam resonator.

and a smaller density of micropore defects [7][8][9], suggests that the modulus of elasticity E of the deposited CVD diamond material is strongly dependent upon the amount of non-diamond carbon, voids, and defects, present in the final film. In addition, since larger grain sizes reduce the boundary areas where non-diamond carbon resides, and given that grain size generally increases with film thickness, a higher E is expected for thicker films, as verified in Table I. Since acoustic velocity goes as $\sqrt{E}$, thicker films with fewer voids and defects should also exhibit higher acoustic velocity.

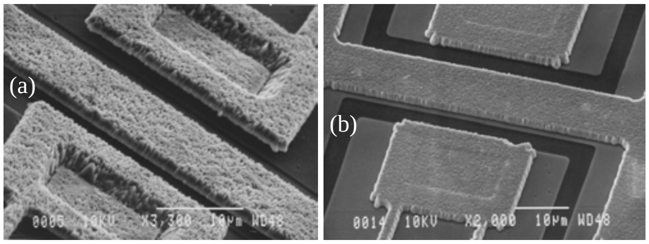

Fig. 5: Close-in SEMs of the etched edges on (a) a TypeC device; and (b) a TypeD device.

A mechanism where film quality plays a significant role in setting E is clearly supported by Fig. 5, which presents close-in SEM shots of TypeC and TypeD devices, showing a substantially smoother, porous-free surface for the better performing TypeD device. The surface roughness seen for the TypeD device is, in fact, comparable to that attainable in previous polysilicon counterparts [10]. On the other hand, pores and voids are clearly visible in the TypeC material, and these then likely contribute to a smaller Young's modulus. As evidence of the degrading impact of non-diamond carbon in the final film, the TypeA recipe lacks a plasma pretreatment step [2], and thus, suffers from poor nucleation and carburization over the substrate before deposition, leading to the lowest acoustic velocity of all recipes in Table I.

In summary, in order to maximize the acoustic velocity of CVD diamond material, the CH_4 reactant concentration should be reduced during deposition, and the temperature increased to maintain a reasonable deposition rate, as was done for the TypeD device en route to the highest reported acoustic velocity so far in a surface-micromachinable material for micromechanical resonators.

IV. CONCLUSIONS

CVD polydiamond with an acoustic velocity as high as 14,252 m/s has been achieved via a low CH_4-concentration deposition recipe and used to demonstrate micromechanical resonators with Q's greater than 30,000 and frequencies substantially higher than those of equivalently sized devices in any other material to date. These results now establish CVD polydiamond as one the strongest contenders among high acoustic velocity materials potentially capable of extending vibrating micromechanical resonance frequencies past 1 GHz for RF communication applications [3].

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