Diamond high speed and high power MEMS switches

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Abstract

Future phased array transmit/receive (T/R) modules require wide bandwidth, low loss switches to replace the circulator at the power amplifier (PA) output. Circulators have inherent drawbacks including high cost, inability to integrate and physical size. Currently protection of the low noise amplifier (LNA) is required because of poor isolation. Consequently a cost, size and weight reduction as well as increased performance are expected when using a T/R switch. Currently no wide bandwidth switches with high power handling capability are available. Field Effect Transistor (FET) implementations lack either power or bandwidth and sacrifice insertion loss. MicroElectroMechanical (MEM) RF switch technology has been demonstrated to exhibit very low insertion loss with multi-octave performance at microwave frequencies however, silicon or GaAs MEMS switches lack high power handling capabilities. As a consequence of the physical properties of diamond, thermal conductivity and hardness, Diamond MEMS offer the potential of outstanding performance. The high Youngs Modulus (stiffness) enables high switching speeds. It has the highest thermal conductivity among solids allowing efficient power dissipation lending itself to the potential integration for high power systems on chip. The University of Ulm is recognized as a center of excellence for Diamond synthesis and device fabrication. Switches are identified in the TDM research theme as a selected topic of high interest to the DTC.

Keywords: Diamond, MicroElectroMechanical Systems (MEMS), Microswitch

Introduction

Diamond is a multi-functional MEMS material with many extraordinary properties. It can be highly insulating (TΩ-cm at R.T.) or quasi-metallic (mΩ-cm) by doping. It is chemically inert and is therefore an ideal wet chemical etch-stop; yet it can be dry etched in an oxygen-plasma very efficiently. It exhibits high stiffness and fracture strength, enabling large contact forces. It is highly temperature stable; and although metastable it will only graphitize above 1500 °C. It has the highest thermal conductivity among solids and will effectively dissipate power losses. It does not form self-passivating and insulating oxides and will only alloy with refractory metals. It is therefore especially suitable for high speed, high power, high temperature and heavy-duty MEMS components such as power switches. A MEMS technology for extreme applications, based on CVD-diamond films, has been evaluated and developed during the last decade by the University of Ulm. This has included bulk machining, surface machining and sacrificial layer technologies (based on SiO_2 or Cu) for high aspect ratio structures. Films are deposited onto large area substrates, and are generally polycrystalline, mostly nano or ultra-nano crystalline with a grain size of approx. 50 to 100 nm or 5 to 10 nm respectively. In most cases the films have been grown on 100 oriented Si substrates by microwave assisted plasma CVD (MPCVD) at 2.4 GHz or hot filament CVD (HFCVD); the key in most cases being to obtain a high density of H-radicals in dilute CH_4. Although these films are in general a composite of diamond nano-grains and a graphitic grain boundary network, the diamond properties are widely preserved. P-type doping with boron can be controlled across approx. 4 orders of magnitude and can reach into the 10^{20} cm^{-3} range, allowing quasi-metallic conduction in the valence band and ohmic contact formation. A number of MEMS structures have been demonstrated, almost exclusively by Ulm. For example: an all-diamond inkjet for dispension of aggressive media [1], an all-diamond membrane pump [2], high G accelerators using a diamond bridge and Si seismic mass [3], a catheter for the heart [4], a cell patch clamp system [5] and various types of diamond cantilever switches [6,7]. These cantilever switches have been the most complex diamond MEMS structures developed to date. They have been constructed as proof-of-concept experiments to demonstrate the extraordinary properties of diamond. Some key features are listed in comparison to other MEMS materials in table 1.

	diamond	nano-diamond	Si (intr.)	(3c)SiC	Ni	Si_3N_4	PZT
Hardness [GPa]	100	100	13	29.6	0.7	~40	~15
Young's modulus [GPa]	1143	≥ 1000	170	450	210	300	80
density [g/cm³]	3.52	3.52	2.33	3.21	8.90	3.18	7.50
breakdown field [10^6 V/cm]	10	10	0.5	3	-	~10	10
electrical Resistivity [Ωcm]	10^{12}-10^{16}	10^8	10^4	10^2-10^6	$7 \cdot 10^{-6}$	$>10^{14}$	$>10^{14}$

Table 1:
Data of various MEMS materials

Actuator Design

As mentioned, diamond is a rather stiff material, as indicated by its high Youngs Modulus. Therefore the mechanical resonance frequency will be high, but high mechanical deflection forces and bending moments need also to be generated by the actuator structure. Here four principle concepts may be considered: 1) electro-static, 2) piezo-electric, 3) electro-thermal, and 4) electromagnetic.

Used in most cases is the electrostatic drive, because of no static losses. However, the driving voltage needs to be applied constantly and may interfere with the signal, if isolation is not perfect. Deflection forces are moderate even for high driving voltages. The piezoelectric principle is mostly used in conjunction with PZT, which is limited by its Curie-temperature to medium temperatures. High contact forces can be developed. The electrothermal bi-metal concept enables to develop high bending moments. The driving voltage can be kept low by the heater design. The switch may be temperature sensitive or not, depending on the heater arrangement. Thus such switches may be designed for high power or as fuse for overdrive protection. The switch can only be operated without static losses in a bistable configuration (leading to a bridge configuration). The electromagnetic concept is mostly bulky and therefore not often employed. Further details can be found in ref. 8 (focussing on diamond).

Here shortly high seed and high power configurations will be addressed.

High Speed Design

Single ended antilever structures are basic structures for fast switching related to the Youngs Modulus, mass density and cantilever geometry. Here, the piezoelectric driving concept has been investigated for the high speed case, to obtain a high deflection force (in connection with the high Youngs Modulus of nanodiamond) and to avoid a standby voltage. Fig. 2 shows the dependence of the mechanical resonance frequency for a diamond/PZT unimorph with the dimensions as listed. It can be seen that thin and short cantilevers are expected to resonate close to GHz frequencies.

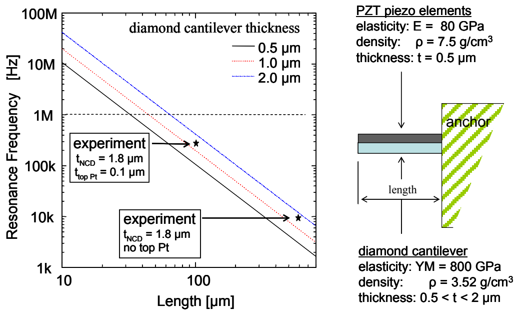

Fig. 2:
Resonance of diamond /PZT cantilever deflection with cantilever length for various cantilever thicknesses with experimental results as described in the text.

Fig. 3 shows such a stack of PZT on nanodiamond with a Pt adhesion interlayer. The film was deposited from a solgel solution and then solidified and poled [9].

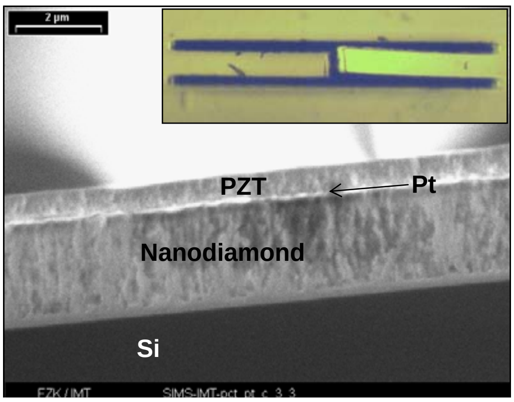

Fig. 3:
Nanodiamond/PZT double layer, and 300 µm x 590 µm cantilever structure (insert).

The beam shown in the insert of fig. 3 has been actuated by an external resonator. The resonance frequency obtained is shown in fig. 2 for the 590µm long cantilever experiment. In a second experiment cantilevers had been fully processed including a Pt top electrode. The experimental point for the 100 µm long cantilever shown in fig 2 represents a resonance frequency of 280 KHz (now including an increased total mass due to the Pt overlayer) of such a fully processed device for actuation with 5 V bias across the PZT layer. Fig. 4 shows a fully processed piezo-cantilever structure with 20 µm beam length. The technology is still very basic, no self-alignment and etchstop processing steps have yet been incorporated. Thus the top Pt electrode does not yet cover the entire cantilever surface. Nevertheless, extrapolating the experimental tendency from fig. 2, a resonance frequency of 7 MHz can be expected.

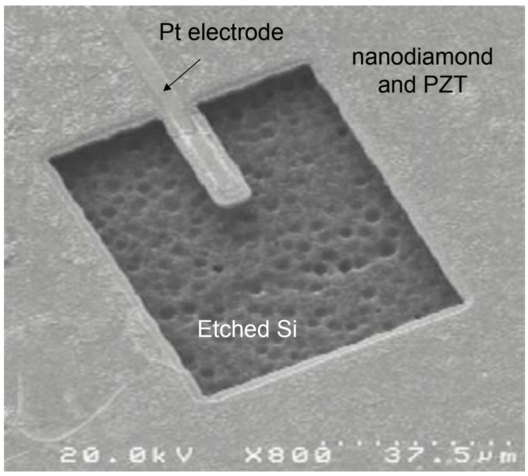

Fig. 4:
Micrograph of nanodiamond/PZT piezo cantilever structure.

Power Switch Design

Cantilever structures like the above discussed ones are usually fabricated on the baseplate by surface and bulk machining processes. However, nano-diamond deposition techniques are usually not compatible with Si-CMOS or GaAs and GaN HEMT technologies and switches cannot yet be integrated monolithically. An alternative would be a hybrid integration concept, where the actuator part is fabricated separately and then mounted into a baseplate circuit, which could be a semiconductor MMIC or dielectric waveguide substrate. This has been obtained with a bistable diamond bridge actuator fabricated in a Si-frame, which is then soldered onto a waveguide substrate.

The switching concept is illustrated in fig. 5 also showing the heater arrangement.

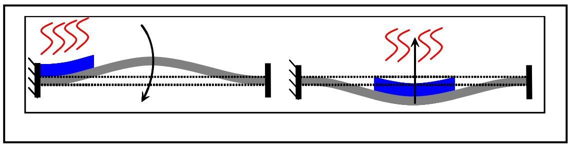

Fig. 5:
Bistable switching of buckled double anchored cantilever by bimetal heating.

The structure relies on the built-in compressive stress between the bridge and the Si-frame. Thus, careful structural design and stress engineering are needed [10]. The switching speed is determined by the mechanical transition time between the two states. In the case shown, the fast thermal power dissipation through the diamond film is not limiting the switching speed. This is shown in fig. 6 for a specific example discussed in ref. [8].

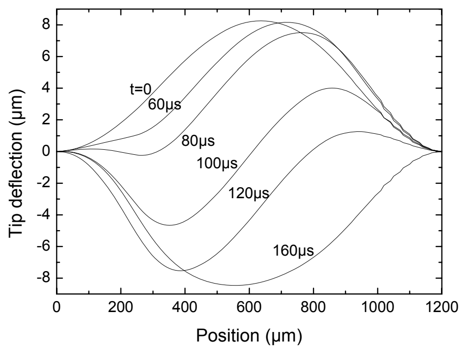

Fig. 6:
Time resolved transition of switching between two stable positions. Overall transition time is approx. 160 µs. After Ref. [8].

The assembly strategy of the actuator and base plate may be illustrated by the two following figs. 7 and 8.

Fig. 7 shows the bridge in the dry etched Si-frame with Cu signal contact in the center and 3 bimetal heater arrangement, two at the outside and one in the center. Also seen are the 4 Cu soldering pads. The actuator is mounted upside down onto a ceramic substrate as illustrated in fig. 8. The soldering technology is based on Cu:Sn and is based on a solid diffusion concept [11]

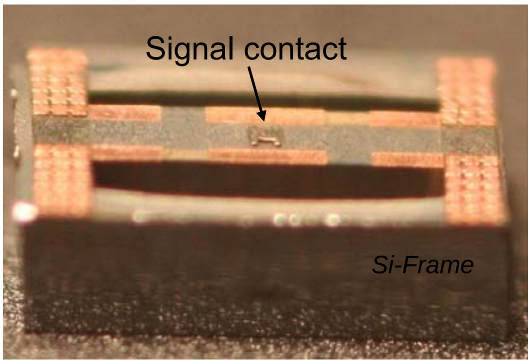

Fig. 7:
Micrograph bridge actuator part, containing the double anchored diamond bridge in a Si frame. After Ref. [13].

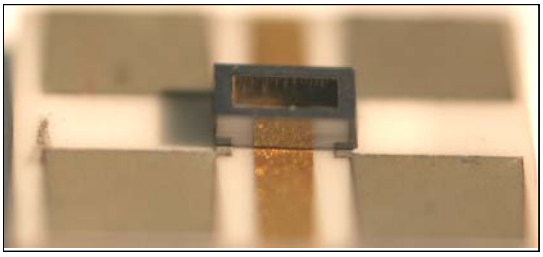

Fig. 8:
Mounted actuator onto waveguide structure on alumina substrate.

For high-power applications the switch was tested in a microstrip waveguide structure at 2.1 GHz [12]. In the on-state power was transmitted up to 47 dBm (45 Watts) without degradation in RF performance (see fig. 9).

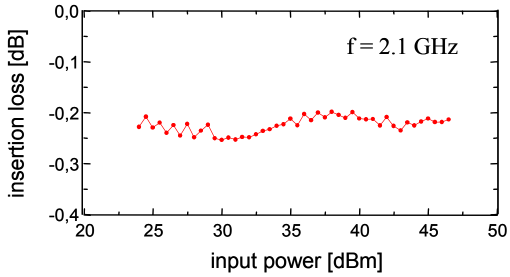

Fig. 9:
Insertion loss of diamond bridge switch up to 45 W transmitted power at 2.1 GHz. After Ref [13].

The power density at both overlapping contact areas was estimated to be in the range of approx. 18 kW/mm^2. The device was still operational after test. This indicates that the generated heat was dissipated effectively and the diamond actuator did not stick to the base plate after this heavy duty operation. The measurement was carried out up to the maximum of available power of the RF supply. Thus, it may be possible to transmit even higher power levels by this device.

Summary

In this paper it has been attempted to evaluate and demonstrate the potential of nanodiamond structures for high speed and high power RF switching applications. Two different actuation principles, the piezo-actuation and the electrothermal drive have been used in the switch design for high speed and high power respectively. In addition two approaches, one based on the monolithic integration of the switch into a base substrate (in this case Si) and an approach for hybrid integration, where the actuator is soldered onto a ceramic baseplate have been compared. A resonance frequency of 280 KHz could be obtained for a 100 μm long piezo-cantilever, and thus 7 MHz are expected for a 20 μm long beam. In the high power case 45 W could be transmitted across a bridge switch structure with 0.25 dB insertion loss and without degradation or sticking. Thus, this comparative investigation shows clearly the versatility of diamond as MEMS material in high performance heavy duty and high speed RF applications.

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