Evaluation of CVD Diamond for Heavy Duty Microwave Switches

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Abstract — **In this contribution the use of CVD diamond as multi-functional material for DC coupled microwave switches is discussed. CVD diamond is a new MEMS material with extraordinary properties especially for heavy duty applications in extreme environments. An all-diamond cantilever based switch is described using two different actuation principles. First results for a coplanar waveguide configuration are presented.**

I. Introduction

The outstanding material properties of diamond like its high hardness, low wear, high elasticity, the absence of any plastic range, high fracture strength, chemical inertness and its high thermal conductivity predestine the material for the use in heavy duty micro electro mechanical systems with high dynamic range. For example, the high Young's modulus leads to high resonance frequencies in membrane and cantilever structures [1]. It can be highly insulating due to its bandgap of 5.45 eV and has been used as transmission line substrate at microwave frequencies [2] and as microwave window for high power mm-wave transmission [3]. It can be quasi-metallic when heavily doped and has been used as heater element in the diamond inkjet [4]. It is thus a multi-functional material and can combine features of ceramic insulators with those of refractory metals, reducing essentially the number of fabrication steps needed in a MEMS structure and reducing the complexity of such devices. All above mentioned features are important in microwave MEMS structures like resonators and switches with low losses.

In this study CVD diamond films have been evaluated for their application in mechanical microswitches. To exploit these properties, a diamond micromachining technology has been developed, which allows monolithic integration of diamond MEMS structures on a diamond-on-silicon substrate. To demonstrate the feasibility an all-diamond switch structure has been developed and adapted to microwave applications.

II. Device Structure

A schematic cross section of the switch structure is shown in Fig. 1, representing a DC-coupled cantilever switch. The cantilever beam structure is realized on a Si-substrate by employing a sacrificial layer technology overgrowing a SiO_2 film [5]. In this basic structure the diamond beam is deflected by electrostatic force; however, in this study two driving principles have been evaluated as described below. The beam is covered by a metal film to reduce conduction losses. The signal contact itself may be metallic or a diamond/diamond contact. The diamond/diamond contact implied that a highly doped tunneling contact has to be designed carefully for low series resistance. However, since diamond is an inert material not alloying or forming an insulating oxide such contacts do not suffer from sticking or contact oxidation. The high Young's modulus yields in a high restoration force, when opening the switch and thus high switching speed. Since most characteristics are almost temperature independent, high temperature operation is possible with constant mechanical properties. Electrostatically activated switching in vacuum has been possible up to 650 °C. Using mechanical deflection, switching operation has been tested up to 850 °C. Assuming a maximum temperature of reliable operation in vacuum of 600 °C, the power handling capability of a cantilever structure as shown in Fig. 8 (top) has been estimated to approx. 5 kW.

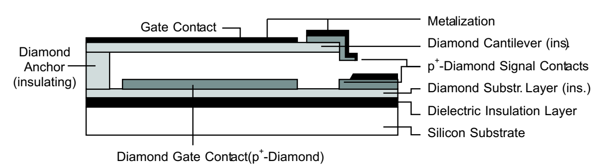

Fig. 1. Schematic cross section of DC-coupled cantilever switch

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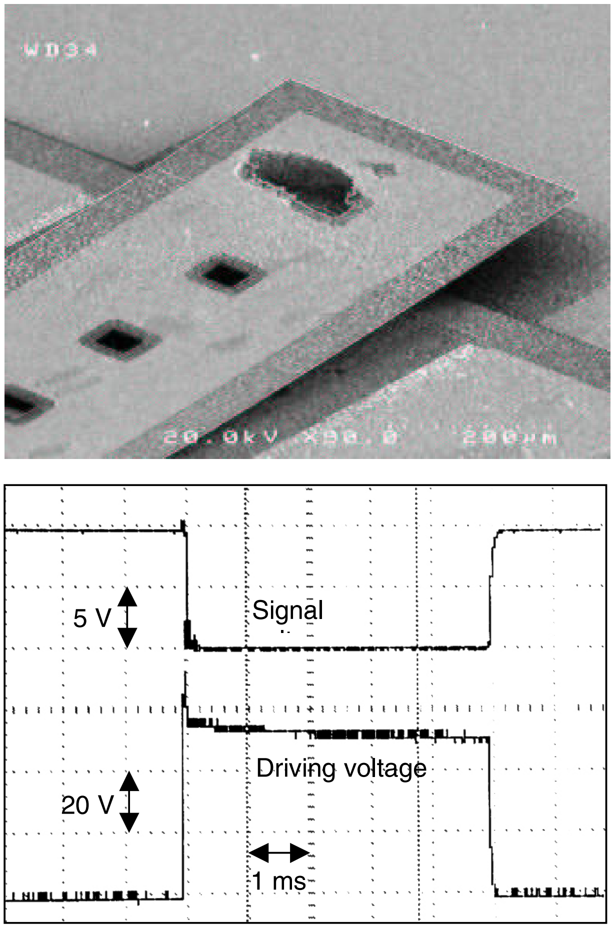

Fig. 2. SEM micrograph and switching characteristics of DC-coupled cantilever switch after heavy overload

III. Driving Principles

Two driving principles have been evaluated: (a) the conventional electrostatic drive, bending the cantilever by applying a driving voltage across a capacitor formed by the beam and a gate plate on the diamond substrate layer. This driving principle has been analyzed in detail and high switching speeds can be obtained in vacuum. The DC switching capability has been tested applying a heavy overload resulting in severe damage of the contact area as shown in Fig. 2, top. However, no contact sticking was observed and the device was still functional afterwards, as shown in Fig. 2, bottom. The disadvantage of this electrostatically driven structure is the high actuation voltage needed, which is also a consequence of the high stiffness of the CVD diamond beam.

Fig. 3. Thermal microswitch in up-state (top and bottom) and down-state (middle), the middle structure is biased.

To circumvent this problem an alternative driving principle, namely the bi-metal effect, was investigated [6]. In this case the beam is partially heated and deflected due to the different thermal expansion coefficient of the two materials, namely diamond (with nearly no temperature dependence) and Ni. Only low voltages are needed to produce a high deflection force. Fig. 3 shows a micrograph of such switches in deflected and undeflected states.

However, permanent deflection also means permanent heating losses. To avoid this problem a bi-stable configuration can be designed, where the beam can be switched between two stable positions. Such a structure is a bridge-like structure consisting of a buckling beam. Buckling is provided by a built-in stress profile in the CVD diamond layer. Fig. 4 shows the principle of operation of this configuration. By a proper placement of the supply metallization, the beam can be heated locally thus producing the appropriate bending moments for up- and down-switching.

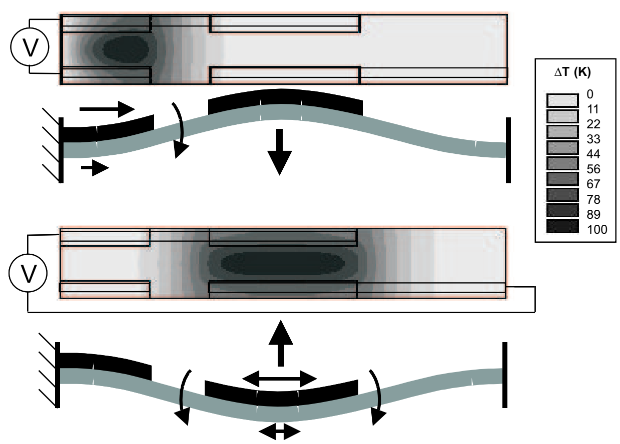

Fig. 4. Layout and basic working principle of bi-stable thermal microswitch

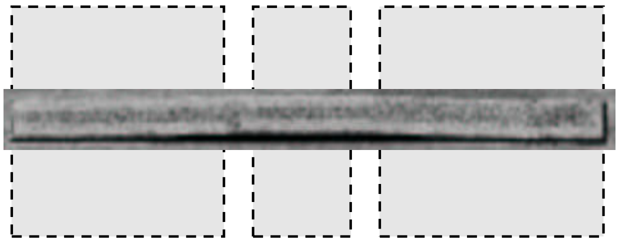

Fig. 5. SEM micrograph of bi-stable, bridge-like switch and artists sketch of a possible Integration in a coplanar configuration

A micrograph of this bridge-like switch layout together with a suggestion for a possible integration of the switch in a coplanar line configuration is given in Fig. 5.

IV. MICROWAVE LAYOUTS AND PERFORMANCE

Switch structures have been realized in coplanar arrangements. In a first step coplanar lines have been evaluated on diamond-on-Si-substrates and diamond membranes (see Fig. 6). Very low losses could be realized, as can be seen in Fig. 7. Two switch layouts are shown in Fig. 8. Firstly this is an in-line switch, which is very similar to the basic beam structure, and secondly a lateral switch. The s_{21}-transmission characteristics of the lateral switch are shown in Fig. 9. In these first experiments the deflection has been mechanically however, due to problems with the high driving voltage of the electrostatic actuation.

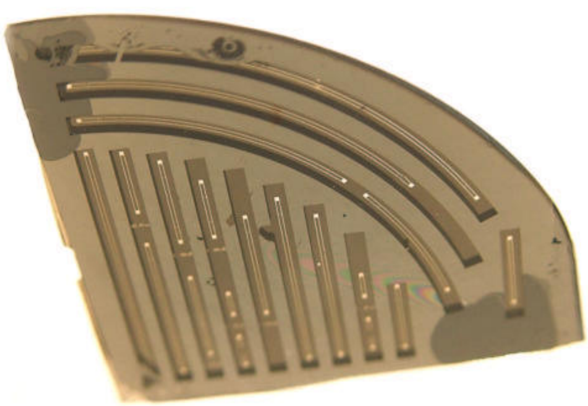

Fig. 6. Coplanar lines on diamond membranes on a ¼ 2" diameter diamond-on-Si substrate

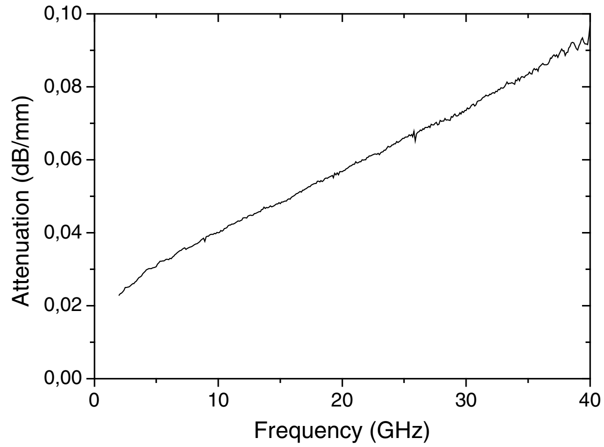

Fig. 7. Loss of coplanar line on diamond membrane (thickness of the diamond layer: 30 µm)

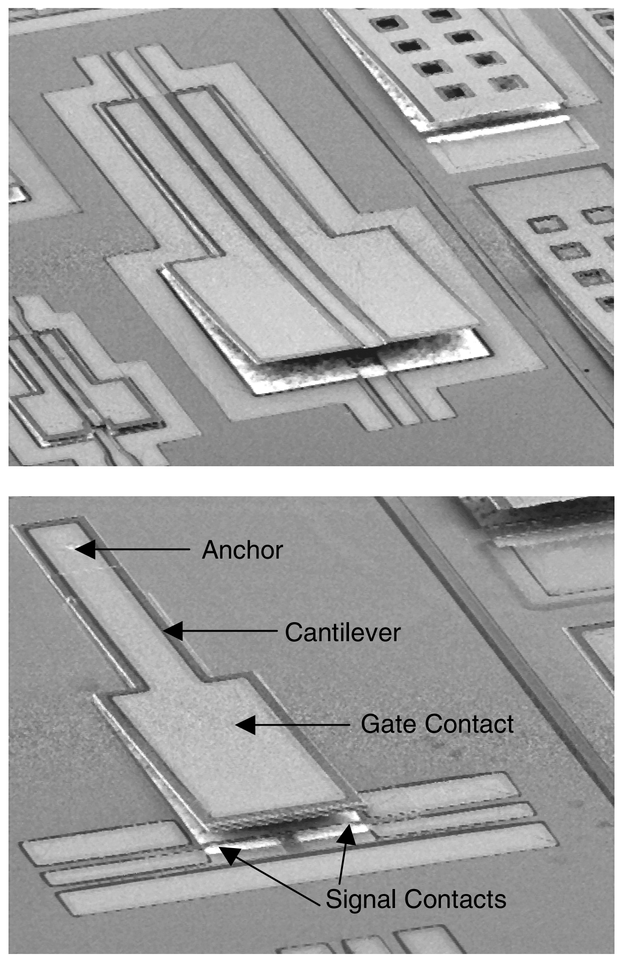

Fig. 8. SEM micrographs of diamond based coplanar microwave switches; beam lengths 2 mm (in-line switch, top) and 1.2 mm (lateral switch, bottom)

As already mentioned this has lead to the development of a bi-stable thermally actuated switch. Such beam structures have not yet been integrated into coplanar lines. However first switching experiments with bridge-like structures have already shown switching from the up-state to the down-state and vice versa by applying a voltage of only 4.0 V and 3.3 V respectively with switching times of 90 µs for opening the switch and 70 µs for closing respectively. This shows that indeed the heat is effectively dissipated through the diamond films.

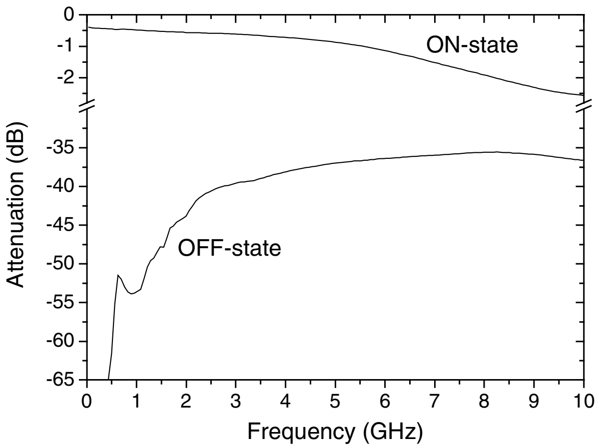

Fig. 9. Transmission characteristics of lateral coplanar microswitch in on- and off-state

V. CONCLUSION

CVD diamond is indeed a new attractive material for high performance heavy duty microwave MEMS components. An all-diamond switch structure has been developed, which is based on a Si-compatible technology. Here diamond is a multi-functional material, reducing complexity, which may in turn improve reliability and lifetime. In this first study the emphasis was on proof-of-concept experiments to verify the expectations rising from the ideal materials properties. Basic cantilever and bridge-like structures have been evaluated and the performance limits estimated. Finally first microwave layouts have been realized and first microwave results have been obtained. All experiments indicate that diamond is indeed well suitable for heavy duty application in harsh environment up to high frequencies.

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