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Diamond microwave micro relay

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Abstract

Based on the technology of the electrostatically actuated cantilever micro switch, entirely made of diamond on a Si-baseplate (except for the final top interconnect metal level) [reported previously] and based on the static and dynamic switching characteristics [reported previously], in coplanar arrangement was designed, fabricated and successfully operated. Due to the DC-coupling the new MEMS-relay allows switching of bias and signal simultaneously.

Keywords: Diamond growth; Diamond MEMS; Micro relay; Micro switch

1. Introduction

Anchored diamond cantilever beam structures have been found to possess extremely attractive properties. The electrostatically activated switching structures using such cantilevers have also been found to reflect many of the extreme diamond properties in their static and dynamic behavior [1–3]. In addition, the possibility of diamond doping allows the use as insulator as well as quasi-metal replacing ceramics, dielectrics and refractory metals concurrently and enables an all-diamond structure. Advantageous device properties, resulting from the use of CVD-diamond films, are, for example: (a) an efficient heat removal, allowing high power and high temperature operation; (b) a high temperature stable Young's Modulus of high value, avoiding fatigue even at high temperatures; and (c) last but not least a quasi-metallic diamond contact surface, avoiding sticking and oxidation and allowing self-cleaning during burn-in due to the highly volatile oxide formation. These features provided the motivation to design a high power switch for microwave applications. The configuration selected was that of a coplanar line (see Fig. 1), where a center signal line is located between two ground planes of high conductivity (mainly using Au as the conducting film) on an insulating substrate like quartz.

In this case a diamond-on-Si technology is used for the switch and the coplanar line is fabricated on a leaky diamond-on-Si-substrate. Thus, substrate losses will limit the operation to the lower GHz-range.

Microwave pulsed power generated by RF-tubes or solid state amplifiers needs to be switched with a high repetition rate. Solid-state switches based on GaAs-FET devices [4] or pin-diodes [5] allow DC-coupling, but suffer from a high on-resistance in the range of typically 2–5 Ω, which limits their power-handling capability. Conventional microwave MEMS-switches are generally capacitively coupled with a low frequency cut-off for transmission [6] and suffer from a limited lifetime if DC-coupled. The diamond switch is thought to be able to combine both the DC-coupling and the high power handling capability.

2. Technology

A schematic cross-section of the relay structure is given in Fig. 2.

The main part is a freestanding diamond cantilever that can be deflected electrostatically by applying a voltage between the cantilever gate contact and the substrate gate contact. In the deflected state, the canti-

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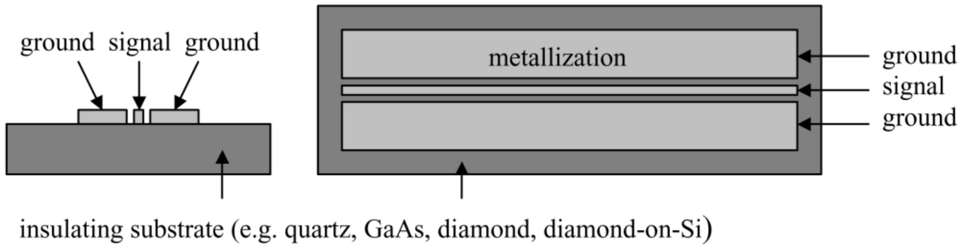

Fig. 1. Schematic design of coplanar line.

lever is bent towards the substrate and current flow across the cantilever signal contact and the substrate signal contact is possible. In the off-state the signal contacts are separated by an air gap.

All substantial parts of the relay are made of CVD-diamond. Thus, heat generated caused by to power loss in the signal contacts can be effectively dissipated over the cantilever and the substrate. Also, no sticking caused by to the melting of metal contacts or formation of insulating oxide layers on the signal contacts can occur.

A new fabrication technology was developed, allowing location of the signal contact at the outer end of the cantilever by selective overgrowth of the cantilever edge with a highly doped cap layer. This contact configuration is an essential improvement, leading to a minimization of both the resistance in the on-state and the capacitance in the off-state.

The on-state resistance is determined by two effects, firstly the narrowing of the contact area at the mechanical contact tip leading to an increase in contact resistance. Optimization of the active diamond contact area was achieved by forming the contacts by applying a DC-current leading to thermal etching of the rough diamond surface under oxygen ambient. A second effect, which substantially determines the on-state resistance, are the series resistances of the doped diamond sheets between the signal contact metallization and the mechanical contact area. These resistances were minimized by bringing the mechanical contact very close to the metallization. Here, a self-aligned deposition technique has been applied.

The off-state capacitance is determined by the air gap and the overlap area of the cantilever and substrate contacts. As the cantilever contact tip is located at the outer end of the cantilever, the overlap area and thus the coupling capacitance could be minimized.

In this design the cantilever is made of highly insulating diamond, allowing galvanic isolation between the gate and the signal contacts and their respective metallizations.

For application as microwave switch, the metallizations were designed in a coplanar con-figuration with an impedance of 50 Ω, as shown in the SEM-micrographs in Fig. 3. Two configurations have been developed, (a) orthogonal-relays with driving cantilevers orthogonally oriented to the coplanar lines (Fig. 3 left) and (b) in-line-relays with the coplanar line oriented parallel to the cantilever.

In the orthogonal relay structure (Fig. 3 left) the coplanar line is located on the substrate and the signal line is disconnected. To electrically bridge the disconnection, two signal contacts, which are electrically connected to the cantilever surface and located at the end of the beam, are used.

In the in-line-relay (Fig. 3 right) the coplanar line is located along the cantilever and only one signal contact is necessary to close the signal line at the end of the beam.

The butterfly wings of the cantilever beam are designed to reduce the threshold voltage.

The optimum geometrical dimensions have been obtained by simulations using a finite element tool.

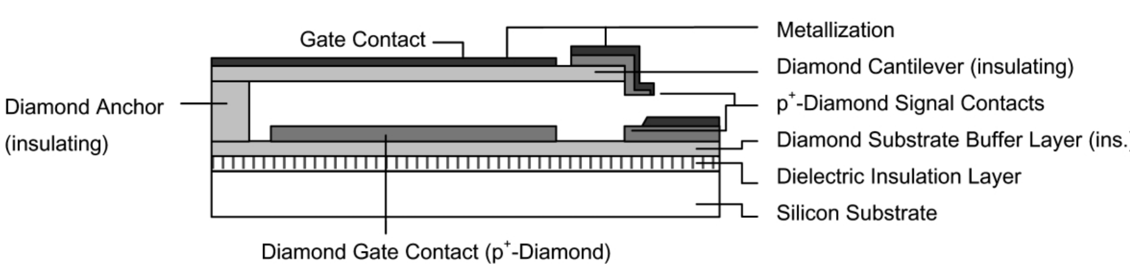

Fig. 2. Schematic cross-section.

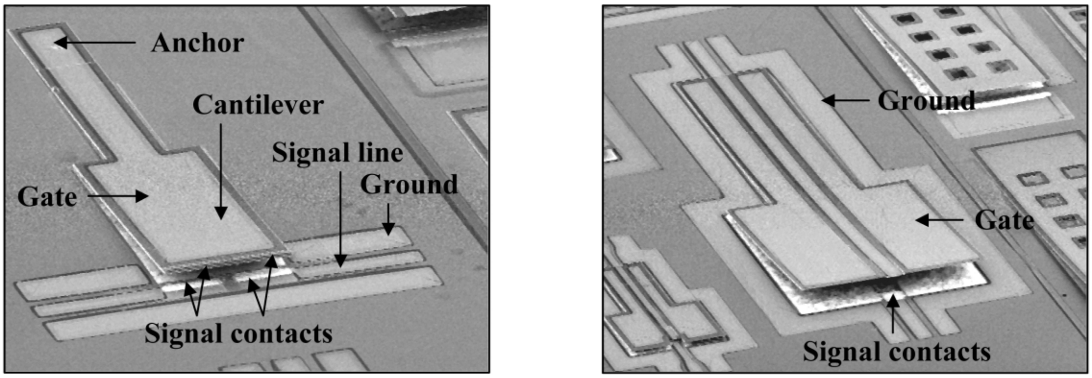

Fig. 3. SEM-micrographs of microwave relay structures (beam length: 2500 μm); left: Coplanar line pattern deposited on the substrate and oriented orthogonally to the cantilever; right: coplanar line pattern deposited onto the beam surface and oriented along the cantilever.

In Fig. 4 an overview of the layout of relay structures with various geometries fabricated on a 1/4 2″ Wafer is shown.

3. Characteristics

As mentioned before, the coplanar relays have been fabricated on a diamond-on-silicon substrate. Due to the penetration of the electrical field of the coplanar line into the electrically conductive substrate, this configuration is expected to lead to a substantial attenuation in the transmission characteristics. To investigate this effect, two coplanar lines with geometrical dimensions similar to the coplanar switch have been fabricated (length: 2500 μm; Si-substrate thickness: 300 μm; specific resistance of the Si-substrate: 10 Ωcm). However, in specific cases the Si-substrate has been removed completely by dry etching to prevent the substrate losses. In Fig. 5 (left) the results of the *s*-parameter measurements of the two lines with and without Si-substrate are shown.

As can be seen, a high and frequency-dependent attenuation can be observed for the diamond-on-Si line. In contrast, a negligible attenuation was observed on the line where the Si-substrate has been removed.

As a result, one can summarize that the coplanar relays fabricated on the Si-substrate are also expected to show a strong attenuation and are, therefore, only suitable for the low GHz-range. To obtain low attenuation characteristics, an insulating substrate (like quartz) or a sufficiently thick insulating layer on top of the Si-substrate is necessary.

In Fig. 5 (right) the transient switching characteristics of a diamond micro relay with an applied DC-voltage is depicted. Depending on the gate voltage, switch-on-times as low as 10 μs could be extracted. The switch-on time decreases with increasing gate voltage. Furthermore, low switch-on times could be obtained by operating the switch under vacuum conditions, where air-damping effects are minimized.

To investigate the high frequency behavior of the relay at microwave frequencies, *s*-parameter measurements from 45 MHz up to 10 GHz have been performed using a HP 8517 A *s*-parameter vector analyzer. In Fig. 6 the absolute value of the transmission characteristics

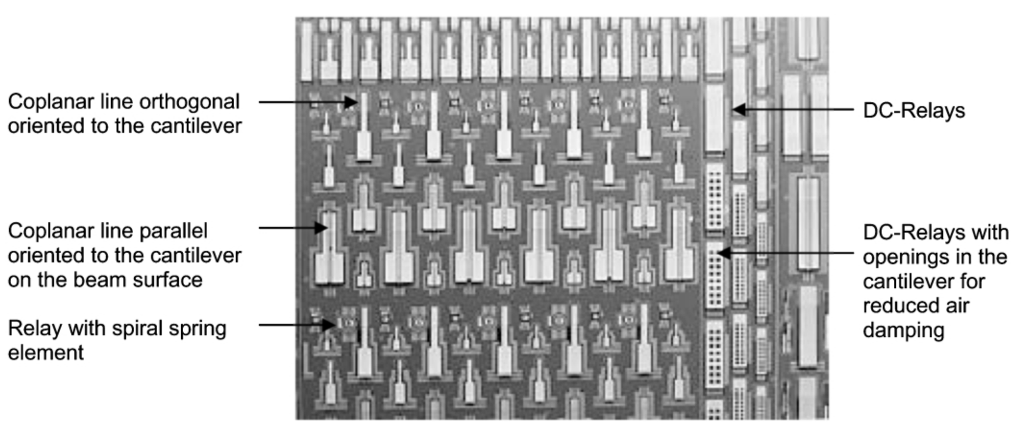

Fig. 4. Part of a 1/4 2″ substrate with differently scaled and designed microwave switches.

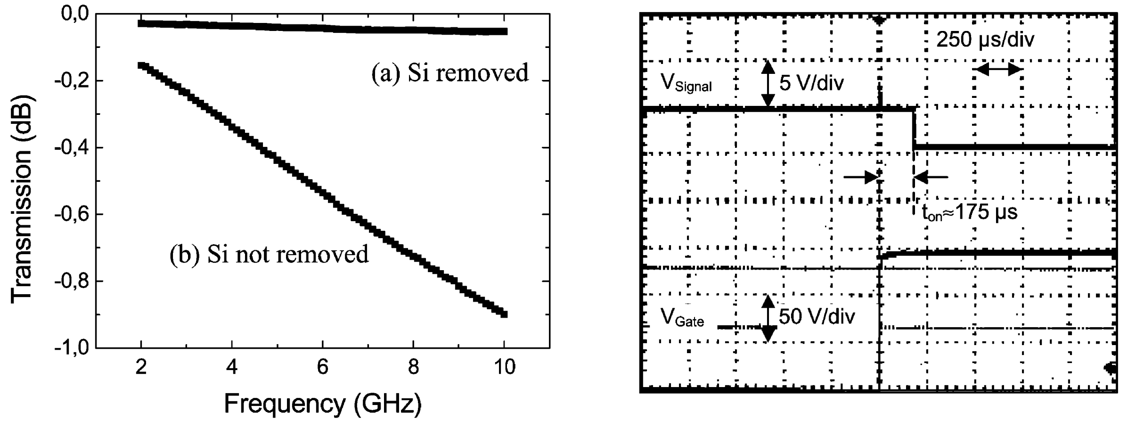

Fig. 5. Left: transmission behavior of coplanar lines on a diamond-on-Si (HOD) substrate: (length: 2500 μm, Si-substrate thickness: 300 μm, specific resistance of the Si-substrate: 10 Ωcm) (a) Si substrate removed below the diamond sheet; (b) Si-substrate below the diamond HOD sheet; right: transient switching characteristic of a diamond micro relay (cantilever length: 1200 μm, air gap: 1.5 μm, cantilever thickness: 3.9 μm.)

(s_{21}) in the on-state (left) and in the off-state (right) of the relay as depicted in Fig. 3 (right) is shown. In the on-state characteristics the transmission shows an attenuation of ~3.4 dB at 10 GHz. At low frequencies (45 MHz) the relay shows an attenuation of ~1.2 dB. The on-state attenuation in the low frequency range is due to a contact resistance of approximately 5 Ω. With a further optimized technology, as described above, a DC-on-state resistance of approximately 200 mΩ has been realized, however, no s-parameter measurements have been performed on such a relay yet.

The effects that contribute to the increase in the on-state attenuation with increasing frequency can be attributed to losses in the Si-substrate (see above) and attenuation of the metallization (thickness 0.3 μm). Here the metallization was thinner than the penetration depth of the RF-signal (skin-depth).

Attenuation in the off-state is mainly determined by the off-state capacitance. Due to intrinsic stresses, the separation distance between the substrate and the cantilever signal contact could be strongly increased. An attenuation of −23 dB has been extracted at 10 GHz.

4. Conclusion

In this work the first application of the diamond micro switch structure in a microwave relay has been demonstrated. The relay was fabricated using an improved technology that allowed location of the signal contact at the end of the cantilever, using a selective overgrowth process to obtain a contact resistance essentially smaller than the line impedance. The nominally undoped cantilever allowed separation of the gate and signal contacts on the cantilever surface and thus the configuration as

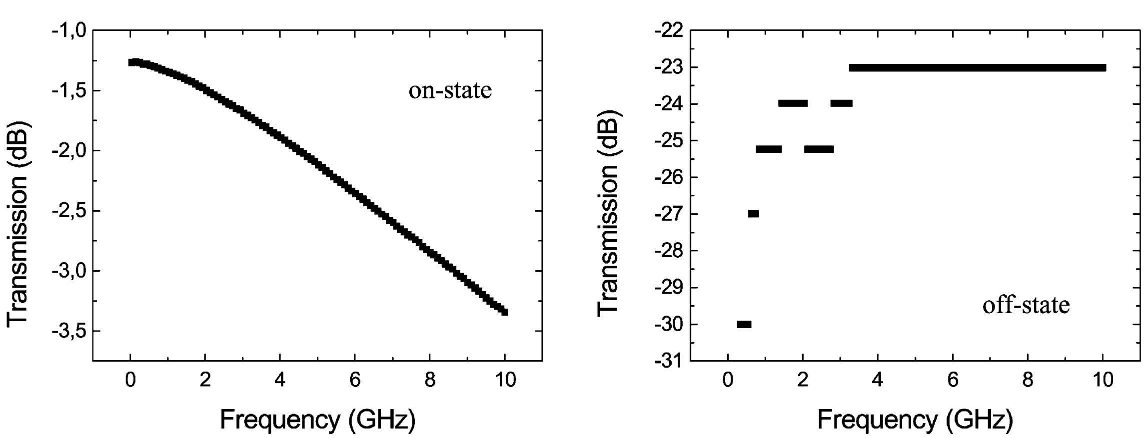

Fig. 6. Left: Absolute value of the transmission in the on-state of a diamond microwave relay; right: absolute value of the transmission in the off-state; length of the relay: 2500 μm.

a coplanar line. From *s*-parameter measurements an on-state attenuation of ~ 3 dB and an off-state attenuation of -23 dB at 10 GHz have been extracted. Further improvements, like a thicker metallization, the removal of the silicon substrate below the relay or the use of an insulating substrate like SiO_2, respectively, is still necessary to reduce the on-state attenuation in the upper GHz range.

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