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Su, Hieng; LLamas-Garro, I; Lancaster, Michael; Prest, Martin; Park, JH; Kim, JM; Baek, CS; Kim, YK

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Performance of RF MEMS switches at low temperatures

H.T. Su, I. Llamas-Garro, M.J. Lancaster, M. Prest,
J.-H. Park, J.-M. Kim, C.-W. Baek and Y.-K. Kim

The actuation voltage of microelectromechanical system (MEMS) metal switches was investigated at temperatures ranging from 10 to 290 K. The investigation shows a 50% increase in the actuation voltage at low temperature. A comparison has been made using a published model and showed similar increment of actuation voltage at low temperature.

Introduction: Over the past few years, radio-frequency microelectromechanical systems (RF MEMS) fabricated using semiconductor micro-fabrication technology have gained significant interest for wireless communication applications owing to their small size, integration capability and superior performance. For instance, using RF MEMS switches, RF circuits such as variable capacitors, tunable filters, phase shifters and signal routers have been demonstrated [1]. Recently, there has been research interest in the application of the high-*Tc* superconductor (HTS) in combination with RF MEMS devices. A switched HTS microstrip resonator and a tunable HTS filter, both incorporating MEMS technology, have been demonstrated [2, 3]. While successful integration of MEMS switches onto HTS devices is a challenging task, the operational issue of RF MEMS switches at low temperatures is another key consideration to many microwave and system designers. In fact, there has been little literature reporting the behaviour of MEMS switches at cryogenic temperature. In this Letter, we report our recent findings on low temperature measurements of MEMS metal switches.

Design of metal switch: The layout of the metal switch is shown in Fig. 1. The metal switches were fabricated on a 0.52 mm-thick quartz substrate. The switches consist of two electrostatically actuated nickel pads and a small central gold-plated nickel RF contact pad. The RF contact pad is electrically isolated and physically connected to the actuation pads by a thin dielectric membrane of silicon nitride. The switch actuates on a gold 50 Ω coplanar waveguide (CPW) of thickness 3 μm, and signal line width 50 μm. Below the RF contact pad of the switch is a 5 μm gap in the signal line. The RF contact pad bridges this gap by direct contact when the actuation voltage is applied. The height of the RF contact pad above the transmission line, before actuation, is 1.2 μm. The two coplanar ground planes are connected via air-bridges. The fabrication process of a similar metal switch has been discussed in [4]. The size of the switch (without the biasing lines) is about 0.5 × 0.32 mm.

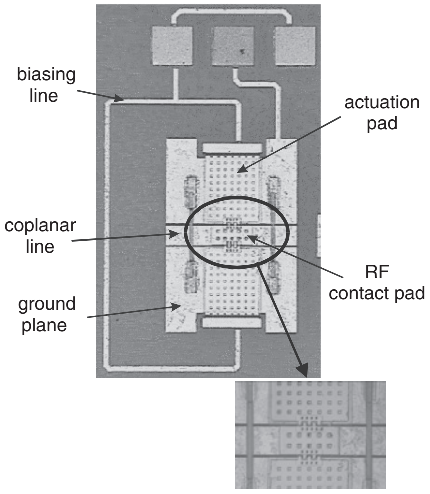

Fig. 1 *Layout of metal switch*

Measurement results: Measurements of the metal switches were carried out using a cryogenic probe station. Two special 90° microwave bent probes [5] with a pitch size of 150 μm were used. Measurements were performed for metal switches on a die. Each switch is slightly different in size in terms of the width and length of the actuation pads compared with others. S-parameters were measured using an Agilent 8722ES network analyser. Calibration was performed at 290 K using Cascade Microtech software (WinCal); the calibration technique used was Thru-Reflect-Reflect-Match (TRRM). The measured insertion losses for three of the switches at room temperature and at 10 GHz were 0.05, 0.16 and 0.14 dB, compared with simulated insertion loss of 0.04 dB. The isolations were in the range of 20 to 30 dB. Measurements were taken at different temperature intervals. At a particular temperature, bias voltage was applied to the metal switch through a DC probe. Actuation voltage was recorded when S_{21} decreased suddenly to close to about 0 dB (switch closed). Fig. 2 shows the recorded actuation voltages for a number of metal switches over the temperature range 290 to 10 K.

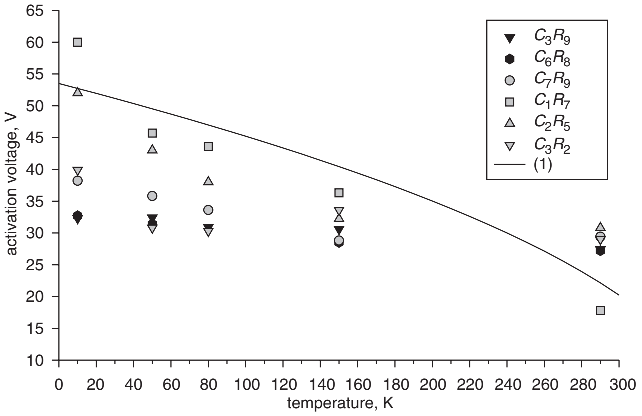

Fig. 2 *Measured actuation voltages for number of switches against temperature and calculated voltages from (1)*

Note that the actuation voltages of the metal switches were increased as the temperature reduced. Most of the switches were actuated at a bias voltage between 30 and 60 V. It was observed that the switches become more difficult to actuate at low temperatures. Goldsmith and Forehand [6] published a simple theoretical model for temperature variation of actuation voltage and reported the same observation of increment in the actuation voltage of MEMS switches as the temperature goes down but their measurements only went down to about −50°C. They attributed the increase in actuation voltage to increasing stress in the actuators, as a result of the difference in thermal expansion coefficients between the metal and the quartz substrate.

An approximate formula to calculate the actuation or pull-in voltage for these metal switches is given by [6, 7]:

$$V_p \cong \sqrt{\frac{64\gamma(1-\nu)tg_0^3}{27L^2\varepsilon_0}(\Delta\alpha E(T_{zs}-T))} \qquad (1)$$

where the geometrical factor $\gamma = 1$, ν is the Poisson's ratio for nickel (0.31), t is the thickness of the nickel (2.5 μm), g_0 is the OFF state gap between the actuation pad and the bottom electrode (1.2 μm), L is the length of the actuation pads (500 μm, assuming they are one piece and measuring from end to end), $\Delta\alpha$ is the difference in thermal expansion coefficient between nickel and quartz (12.8×10^{-6} K^{-1}), E is the Young's modulus for nickel (200 GPa), $T_{zs} = 350$ K is the effective temperature of zero stress in the nickel (dependent on deposition temperature and as-deposited stress), T is the operation temperature and ε_0 is the permittivity of air. Equation (1) assumes that the actuators are solid bars and so would tend to overestimate the true value as the actuators have hinged sections to allow easier bending.

Fig. 3 shows an example of measured insertion loss and isolation up to 20 GHz at 290 and 80 K. At 290 K, the switch actuated at 29 V, the actuation voltage increased slightly to 30 V at 80 K. The ripples at 80 K measurements are due to calibration as the calibration was performed at 290 K.

An important design consideration is to know the percentage of switches that worked at low temperatures if the switches are to be used with superconducting microwave devices. In this experiment, a total number of 28 switches were measured. It was revealed that at 290 K about 82% of the switches actuated, and this decreased to 39% at 80 K and further at lower temperatures. If we consider only working switches at 290 K, about 48% of these switches worked at 80 K.

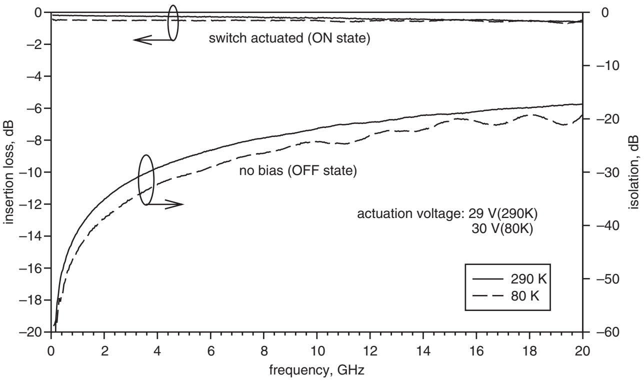

Fig. 3 *Example of measured insertion losses and isolations at 290 and 80 K (switch C_3R_2)*

Conclusion: Low-temperature performance of MEMS metal switches has been investigated. Measurements showed an increase in the actuation voltage as the temperature went down to 10 K. It was found that the working percentage of these switches decreases at low temperature.

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H.T. Su (*School of Engineering, Swinburne University of Technology, Malaysia*)

I. Llamas-Garro (*Large Millimeter Telescope, National Institute for Astrophysics, Optics and Electronics, Mexico*)

E-mail: llamasi@iee.org

M.J. Lancaster and M. Prest (*School of Electronic, Electrical and Computer Engineering, The University of Birmingham, United Kingdom*)

J.-M. Kim and Y.-K. Kim (*School of Electrical Engineering and Computer Science, Seoul National University, Seoul 137-724, Korea*)

J.-H. Park (*LG Electronics Institute of Technology, Seocho-Gu, Seoul 137-724, Korea*)

C.-W. Baek (*School of Electrical and Electronics Engineering, Chung-Ang University, Korea*)

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