NEMS Electrostatic RF Wakeup Switch with Pt FIB Contact

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Abstract. Recent pushes to reduce wireless sensor node power consumption have targeted sensors detecting the signal of interest, e.g. acoustic, acceleration, rotation, and use the energy in the signal to trigger switches. Regardless of the sensing modality however, all wireless sensors include some form of data communication radio, which in many cases is constantly consuming power. We take inspiration from a very low sub-threshold current and low switching-energy NEMS switch to implement a near zero-power laterally actuated NEMS electrostatic RF wake-up switch to reduce passive power draw by the RF electronics [1]. The switch is operated by holding a mechanical contact gap just outside of thermal fluctuations and an RF signal acts to physically close the switch. Focused ion beam is utilized to achieve sub-100 nm platinum contact gaps, allowing for below 3V operation and improved reliability. Preliminary results are presented from a custom vacuum probe station utilizing a switch position control loop for the contact-based switch operating off resonance.

1. Introduction
As the proliferation of stand-alone sensor nodes continues, power reduction of all components becomes increasingly important to the longevity of individual sensors and reliability of sensor networks as a whole [2]. In particular, for applications with infrequent events of interest, significant power savings can be gained from operating in an asleep-yet-aware mode of near-zero power consumption. Only upon receiving an appropriate wake-up signal will power hungry electronics (e.g. a microcontroller) be turned on. Many approaches to achieve this type of operation have been developed for physical sensors, for example, vibration, acoustic or magnetic, owing to advancements in piezoelectric MEMS sensor design [3-5]. These sensors have also been used to demonstrate successful wake-up of power-hungry electronics [6-8]. However, much less work has been done to implement this behavior in other sensor node components where the benefit would be just as beneficial, such as the RF electronics, which must be constantly sensing just like other sensors.

Much work to develop such near-zero power RF-wakeup sensors has been implemented in CMOS rectification circuits using a combination of envelope detectors and comparators after down-converting RF or using added external transformers and filters. Many of these have tradeoffs between power consumption and sensitivity, while achieving sub-100nW power consumption even at -40 dBm [9]. Recently, CMOS based switches have been developed offering < -60 dBm sensitivity for less than 10 nW [10, 11].
While MEMS approaches excel for physical sensors, their application regarding RF is much less common. Vitale et al. showed a shunt RF capacitive switch reaching -30 dBm including RF gain through a coplanar waveguide operating at 12.6V, but sensitivity was limited by thermomechanical noise [12]. Wu et al. demonstrated an AlN-based resonant switch that achieved 0.3 pW in the off state and a sensitivity of -4 dBm on resonance [13]. Taking inspiration from a near-kT lateral NEMS switch (300μV switch with ~50V DC bias) [1], we develop a switch achieving both low power consumption through a similar electrostatic design and low DC bias requirement through a novel focused ion beam (FIB) process, while maintaining reasonable RF sensitivity.

2. Device Concept
The switch is comprised of a released shuttle, a set of bias electrodes for setting the DC position of the switch, an RF electrode for the incoming wake-up signal, a contact electrode to sense if the switch has closed, and a reset electrode. When voltage is applied to the DC and RF electrodes, an electrostatic force moves the shuttle towards the contact electrode. Switch operation starts by biasing the DC bias electrodes to bring the shuttle almost into contact with the contact electrode (within a few times the thermal noise). The RF signal is then applied at the RF electrode to fully close the switch. At no point does the device reach pull-in due to the design of the gaps. A small bias voltage on the contact provides a current to the grounded shuttle upon switch closure, which can be read out by a TIA. The switch position in equilibrium with DC bias only, \( z_{DC} \), can be solved for by Eq. 1 where \( k \) is the spring constant of the released shuttle, \( h \) is the shuttle thickness, \( L_{DC} \) the DC electrode overlap length, \( g_{DC} \) the natural gap between shuttle and DC bias electrodes, and \( V_{DC} \) the DC bias itself.

\[
k_{DC} z_{DC} = \frac{1}{2} \frac{\varepsilon_0 W L_{DC}}{(g_{DC} - z_{DC})^2} V_{DC}^2
\]  

To get the best RF sensitivity, the switch DC bias position should be as close as possible to closing, limited by thermal fluctuations. Eq. 2 shows an additional constraint on \( z_{DC} \) due to this condition where \( g_c \) is the natural gap at the contact, \( z_n \) is the thermal displacement noise, \( k_B \) is the Boltzmann constant, \( T \) is temperature, \( Q \) is the quality factor of the device and \( \alpha \) is a safety factor which adds a buffer between the on-resonance thermal fluctuations and the switch being closed.

\[
z_{DC} = g_c - z_n = g_c - \alpha \sqrt{\frac{4 k_B T Q}{k}}
\]  

Finally, the incoming RF signal must close the switch by moving the shuttle rest of the way. Eq. 3 shows the RF electrostatic force and the RF voltage required to close the switch (ignoring any contact due to thermal fluctuations) where \( g_{RF} \) is the natural RF shuttle gap, \( L_{RF} \) is the RF electrode overlap length and \( V_{RF} \) is the RF voltage.

\[
F_{RF} = \frac{Q}{2} \frac{\varepsilon_0 W L_{RF}}{(g_{RF} - z_{DC})^2} V_{RF}^2 = k \alpha \sqrt{\frac{4 k_B T Q}{k}}
\]  

For off-resonance operation, both the RF force and thermal fluctuations will be reduced by the quality factor \( Q \). Bandwidth is assumed equal to resonant frequency for these calculations. For off resonant operation and our device parameters, an estimated RF sensitivity limit of about -30 dBm is predicted.
3. Fabrication

A single photomask process is used to fabricate the switches on a silicon-on-insulator (SOI) substrate. An ASML deep UV stepper is utilized to achieve 300nm gaps at the contact point. Piranha immediately after DRIE or EKC at a later time is used to remove the fluoropolymer remaining from the etch. Before release, platinum contacts and gaps are defined by focused ion beam (FIB). Two approaches are utilized to accomplish this. The first completely covers the contact gap with a layer of Pt, depicting top down, and then cuts a very small gap. This intrinsically deposits Pt on the oxide at the bottom of the contact gap. The second approach deposits at an angle, avoiding Pt deposition on the oxide and creates a gap on each corner of the gap. After Pt deposition and cutting, the device is released in vapor HF. Fig. 2 shows a schematic depiction of the fabrication process through the final release.

Various contact types were investigated, including single and multiple contact points of varying width. Fig. 3 shows an example of a 3-tip contact before and after modification with Pt. Sub-100nm features with 10nm resolution are achievable using the FIB process. The addition of this Pt decreases the natural contact gap, reducing the required DC voltage required and reducing power consumption. Furthermore, Pt acts as a superior contact material with improved reliability and conductivity.

4. Testing

Once released, testing was performed using a custom-built vacuum probe station (Fig. 4A). An example image of a device under test can be seen in Fig. 4B. A control loop is implemented using an Arduino and Python code to control the DC supply (MAXIM5318 18-bit DAC), RF source (R&S SMC100A), and TIA (SR570) for sensing while allowing for fast application of reset pulses to limit contact degradation. Ultimately, these functions can be placed onto a low-power ASIC. The control flow is depicted in Fig. 5.

Testing is accomplished by first ramping the DC voltage to find the turn-on. The DC voltage is then decreased by single DAC steps until a stable shuttle position is reached. From this point, an RF detection test is run by the application of RF of varying amplitudes to find the probability of

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**Figure 2.** Schematic of device fabrication. The two types of Pt application are shown as (a) and (b) on the same released area for simplicity.

**Figure 3.** A) A three-tip contact as fabricated before release. B) Contact after FIB Pt deposition and gap definition. Inset shows single contact with <100nm gap.

**Figure 4.** A) Custom vacuum probe station. B) Device under test with probes landed.
detection (POD). Alternatively, for various switch positions (bias voltages), if no RF is applied, the false alarm rate (FAR) can be measured. After any switch contact a reset pulse is applied and DC voltage is re-ramped. The probe station allows for testing in vacuum and in air or nitrogen. An example RF test showing the DC bias voltage and TIA output voltage is shown in figure 6, as would be typical for the testing setup.

5. Experimental Results
False alarm rate tests are presented for devices operated off resonance. The FAR in vacuum is shown as a worst-case scenario. Furthermore, devices are operated in a non-ideal two-terminal mode with pull-in induced contact occurring between the shuttle and RF electrodes, resulting in theoretical sensitivity less that that discussed above. Fig. 7 shows the FAR in triggers per hour as a function of DC bias voltage for a device with turn-on slightly above 1.36V. As the bias is decreased, the contact point gap is increased, resulting in a significant decrease in FAR. As the voltage away from turn-on approaches 30 mV the FAR goes below 15 false alarm per hour. Passive current consumption for the device is less than 0.05 pA, giving an off-state power consumption of about 70 fW.

POD tests are still underway through optimization of the testing control loop and testing parameters. However, RF detections down to -25 dBm off resonance have been observed and are currently being fully characterized.

6. Conclusions
A MEMS RF wake-up switch with a novel FIB process for platinum contacts is presented. The switch operates at 1.36V with 70 fW passive power consumption with <15 false alarm per hour at approximately -20 dBm. The power required to control the switch is not included in this budget, but can be <10nW with low power and low-speed operation of equivalent CMOS circuits. Switch events down to -25 dBm have been observed, but quantitative probability of detection tests need to be acquired with enough number of samples for statistical significance.

Beyond POD measurements, significant improvements to the switch can help lower the ultimate minimum detectable RF level of the switch. Operating on resonance, exploiting the
$V_{AC} V_{DC}$ electrostatic force term by applying the DC voltage to the shuttle, and operating in a true three-terminal mode will all positive affect sensitivity.

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