Micro-Electro-Mechanical Diode for Tunable Power Conversion

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Technical Report No. UCB/EECS-2016-157
http://www2.eecs.berkeley.edu/Pubs/TechRpts/2016/EECS-2016-157.html

October 5, 2016

Micro-Electro-Mechanical Diode for Tunable Power Conversion

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Research Project

Submitted to the Department of Electrical Engineering and Computer Sciences, University of California at Berkeley, in partial satisfaction of the requirements for the degree of **Master of Science, Plan II**.

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October 4, 2016

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Abstract

Semiconductor diodes suffer from non-idealities in performance, particularly non-zero forward voltage and reverse leakage current, which limit the energy efficiency of power conversion circuits. In this work, a micro-electro-mechanical (MEM) relay configured as a diode is investigated for power conversion application. Specifically, the utility of a MEM diode is demonstrated in a half-wave rectifier circuit. Due to high native pull-in voltage and high ON-state resistance, MEM relay technology requires further refinement to be promising for low-loss power conversion application.

In Loving Memory of Clarence Eugene Polke

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Acknowledgements

I would like to thank my research advisor, Professor Tsu-Jae King Liu, who has provided invaluable advice and mentorship during my time thus far at the University of California, Berkeley. Without her patience, expertise and guidance, I would not have been able to achieve the same level of success in my graduate studies. I have learned very much from her – both in and out of the field of electrical engineering – and I look forward to continued collaboration for the future.

Additionally, I would like to thank the entire King Research Group for the joint efforts required to conduct this research. In particular, I am grateful for the electrical characterization training from Dr. I-Ru Chen and Dr. Yenhao Chen; the circuit setup and microfabrication lessons from Dr. Chuang Qian, Dr. Alexis Peschot, and Dr. Kimihiko Kato; and the numerous discussions with Dr. Bivas Saha, Ms. Urmita Sikder, Dr. Nuo Xu, Ms. Xi Zhang, Ms. Zhixin Ye, Dr. Peng Zheng, Mr. Fei Ding, Mr. Yi-Ting Wu, and Dr. Daniel Connelly. Likewise, I appreciate the assistance in measurements from my former students, Mr. Liam Dougherty, Mr. Brandon Wong and Mr. Javier Wong.

I would like to acknowledge my mentors Dr. Frances Williams, Dr. Sharnnia Artis, Dr. Jeremy Waisome, and Ms. Jelece Morris, who are responsible for introducing me to the field of engineering and have encouraged me during periods of difficulty. Furthermore, I would like to acknowledge the support of EECS faculty and staff, Dr. Sheila Humphreys, Mrs. Tiffany Reardon Quiles, Ms. Meltem Erol, Dr. Gary May, Ms. Victoria Parker and the Black Graduate Engineering and Science Student Association (BGESS). Notably, I would also like to acknowledge the financial support of the Ford Foundation, National Science Foundation, National GEM Consortium, and the University of California.

I especially would like to thank my family – Babajide, Teresa, Omoniyi, and Folakemi – for all of their love and support throughout my life. Finally, and most importantly, I would like to thank God for blessing me with this opportunity to learn and grow.

Chapter 1. Introduction

Rectifiers are commonly used for power conversion circuits, for example to convert an alternating current (ac) power supply to a direct current (dc) power supply. An ideal rectifier should have (nearly) zero forward voltage (V_F) and zero reverse current (I_R) to minimize loss from the peak input voltage to the peak output voltage. In practice, however, silicon-based diodes are used as rectifiers and have a significant built-in voltage (so that V_F is approximately 0.7 V for p-n junction diodes and 0.3 V for Schottky diodes) as well as non-zero I_R.

1.1 Conventional Semiconductor Diode Characteristics

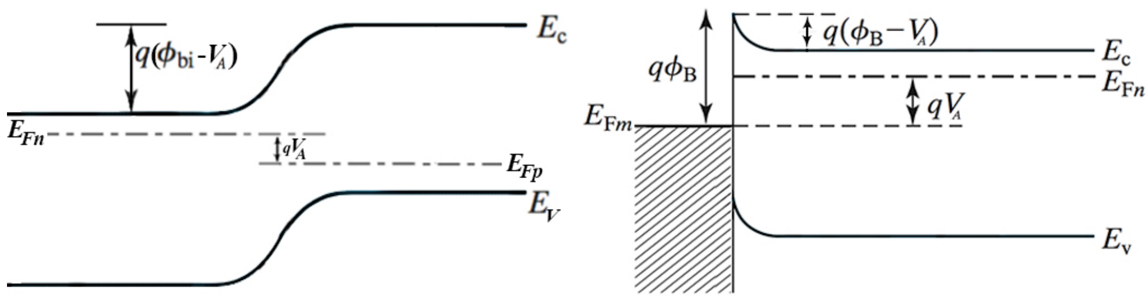


Fig. 1. Energy band diagrams corresponding to (a) p-n junction and (b) metal-semiconductor junction [1].

Conventional semiconductor diodes can be classified into two categories: p-n junction diodes and metal-semiconductor Schottky diodes. The current flow mechanisms for p-n diodes are carrier diffusion due to concentration gradient and carrier drift due to the electric field within the depletion region [1]. Under forward bias ($V_A > 0$), the potential barrier is decreased linearly with increasing applied voltage, thereby increasing the diffusion current exponentially in accordance with Fermi-Dirac statistics. Under reverse bias ($V_A < 0$), the potential barrier is increased with increasing applied voltage, so that negligible diffusion current flows; only a small drift current flows, limited by the rate of minority carrier diffusion into the depletion region. Thus, the diode exhibits rectifying behavior (allowing current to flow more easily in one direction than the other). Similarly, in a Schottky diode, forward biasing reduces the potential barrier to carrier diffusion from the semiconductor into the metal, causing current to increase exponentially with increasing applied voltage; reverse biasing increases the potential barrier and only a small current flows due to thermionic emission of carriers over the Schottky barrier into the semiconductor.

The ideal current expressions for p-n and Schottky diodes are given in equations (1) and (2), respectively [1].

$$I_{p-n} = qA\left(\frac{D_N}{L_N}\frac{n_i^2}{N_A} + \frac{D_P}{L_P}\frac{n_i^2}{N_D}\right)\left(e^{qV_A/kT} - 1\right), \quad (1)$$

$$I_{Schottky} = A\mathcal{A}^*T^2\left(e^{-\Phi_B/kT}\right)\left(e^{qV_A/kT} - 1\right), \quad (2)$$

whereas q is the fundamental charge, $\mathcal{A}^*$ is Richardson's constant, A is the junction area, D_N and D_P are the respective electron and hole diffusion constants, L_N and L_P are the respective electron and hole minority carrier diffusion lengths, N_A and N_D are the net dopant concentrations on the respective p-side and n-side, n_i is the intrinsic carrier concentration, k is the Boltzmann constant, T is the absolute temperature, Φ_B is the Schottky barrier height and V_A is the applied voltage.

The forward voltage V_F required to turn ON a semiconductor diode is somewhat smaller than the built-in potential barrier (which in turn is determined by the n-side and p-side dopant concentrations) in a p-n diode or the Schottky barrier height in a Schottky diode. The current-*vs*.-voltage (*I*-*V*) characteristics of semiconductor diodes are qualitatively compared against the characteristics of an ideal diode in Figure 2.

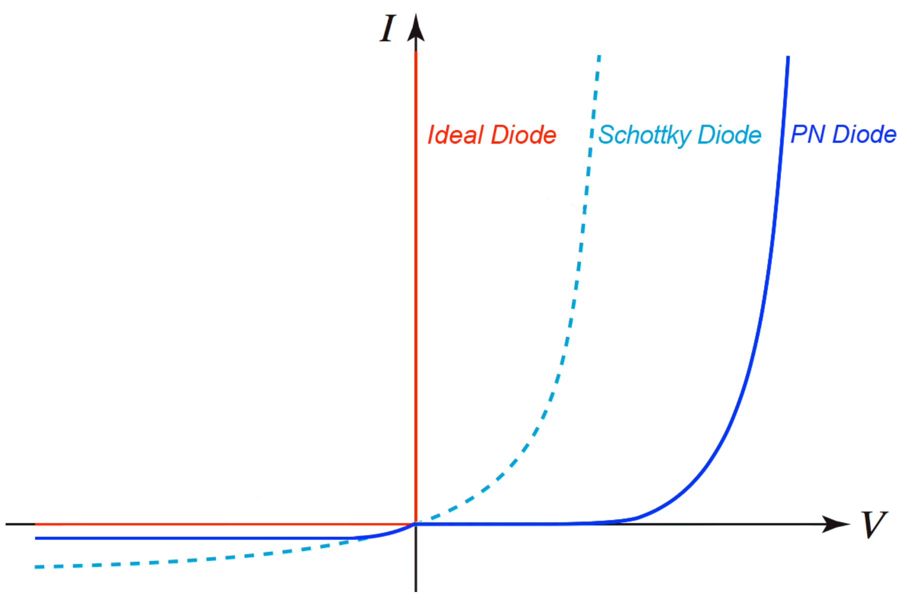


Fig. 2. Qualitative illustration of rectifying characteristics for ideal, Schottky, and p-n diodes.

There is a fundamental trade-off between small V_F and small I_R for semiconductor diodes, as $|I_R|$ is exponentially larger for a diode with linearly smaller V_F; this non-ideal behavior results in rectifying circuit operating power loss. In this work, a micro-electro-mechanical

(MEM) diode is demonstrated to be able to achieve a nearly ideal *I-V* characteristic. The advantages and trade-offs of utilizing a MEM diode for power conversion are investigated in this work using a half-wave rectifier circuit.

Chapter 2. MEM Relay Overview

2.1. MEM Relay Design and Operation

The MEM relay technology developed in [2] has been demonstrated to be well-suited for low-power digital integrated circuit (IC) applications [3] at switching frequencies up to ~100 kHz [7] and is used in this work. Figure 3 illustrates the MEM relay structure.

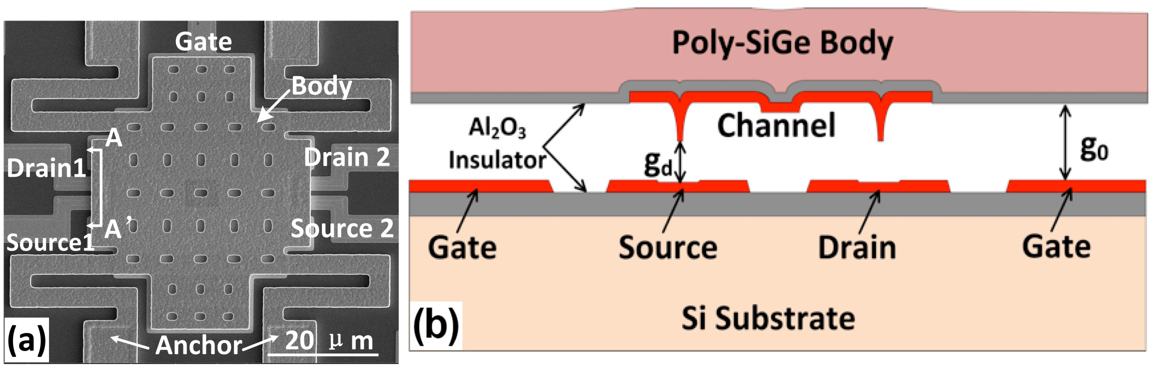


Fig. 3. MEM relay design for IC applications: (a) plan-view scanning electron micrograph, (b) schematic AA' cross-section [4][5].

When the magnitude of the applied gate-to-body voltage (V_{GB}) is larger than that of the pull-in voltage (V_{PI}), the electrostatic force is sufficient to actuate the body downward such that the channels (narrow metal strips attached to the underside of the body via an insulating dielectric layer) come into physical contact with their respective source and drain (S/D) electrodes, thus allowing current (I_{DS}) to flow instantaneously. When V_{GB} is lowered back down below the release voltage (V_{RL}), the spring restoring force of the folded-flexure suspension beams actuates the body upward, such that contact between the channels and their respective S/D electrodes is broken; as a result, I_{DS} abruptly drops to zero.

2.2. Ambipolar Switching Characteristics

Because electrostatic force is attractive no matter the polarity of the applied actuation voltage, a relay can operate with either positive or negative applied gate voltage, *i.e.* its I_{DS} - V_G characteristic is symmetric about 0 V [6]. However, if a non-zero body bias voltage (V_B) is applied to pre-actuate the body downward, the I_{DS} - V_G characteristic becomes asymmetric; smaller gate voltage (V_G) of the opposite polarity is needed, as shown in Figure 4(a) − whereas larger V_G of the same polarity is needed − to switch ON the relay.

2.3. Body-Biasing Effect

By applying $V_B = -V_{RL}$, the magnitude of the positive gate switching voltage is reduced to the hysteresis voltage $V_H \equiv V_{PI} - V_{RL}$, whereas the magnitude of the negative gate switching voltage is increased to $V_{PI} + V_{RL}$. **Therefore, by connecting the gate electrode to the drain electrode, a body-biased relay can operate as a diode with V_F as low as V_H and $I_R = 0$**, with a reverse breakdown voltage $V_{BR} = -(V_{PI} + V_{RL})$. To minimize V_H, the relay should be designed for non-pull-in (NPI) mode operation, *i.e.* the as-fabricated actuation air-gap thickness (g_0) should be at least 3× the as-fabricated contact air-gap thickness (g_d). It should be noted that V_H is always > 0, due to contact adhesive force.

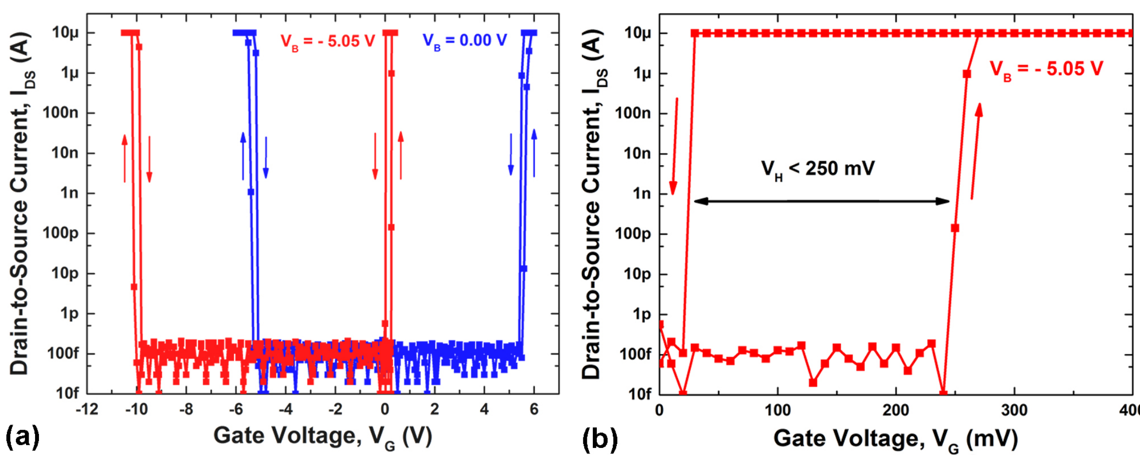


Fig. 4. Measured relay *I-V* characteristics demonstrating that (a) a body bias voltage (V_B) can be used to reduce the gate voltage (V_G) of the opposite polarity required to switch ON the relay, and (b) very small hysteresis voltage (V_H) can be achieved. The ON-state current is purposely limited to 10 μA to avoid contact welding under dc current stress during measurement. In practice, the ON-state resistance can be < 1 kΩ per contact [7].

The measured *I-V* characteristic in Figure 4(b) demonstrates that small V_H (< 250 mV) is possible. It should be noted that the circuit designer can easily adjust V_{PI} by changing the structural dimensions, *e.g.* the length L of the suspension beam, to tune $|V_{BR}|$ over a wide range. (V_{PI} is proportional to the square root of the effective spring constant k_{eff}, and $k_{eff} \propto L^{-3}$.) It also should be noted that a metal-oxide-semiconductor field-effect transistor (MOSFET) can be similarly operated as a diode by electrically connecting its gate and drain electrodes. However, the MOSFET diode forward current increases more gradually, as a function of $(V_G - V_T)^2$ where V_T is the threshold voltage; also, it has relatively small $|V_{BR}|$ (~0.5 V) since the drain junction is forward-biased when the "diode" is reverse biased.

Chapter 3. MEM-Diode Rectifier Circuit Configuration and Operation

3.1. Half-Wave Rectifier Circuit

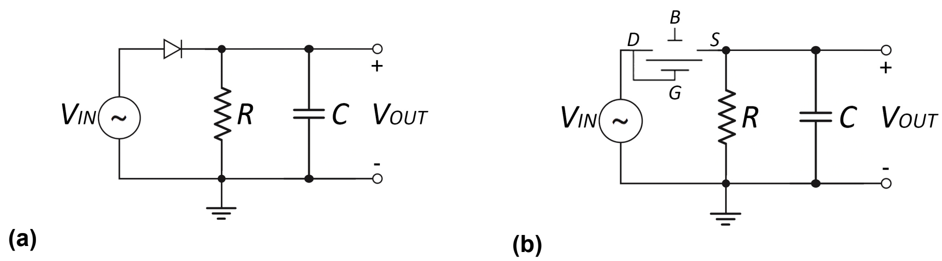
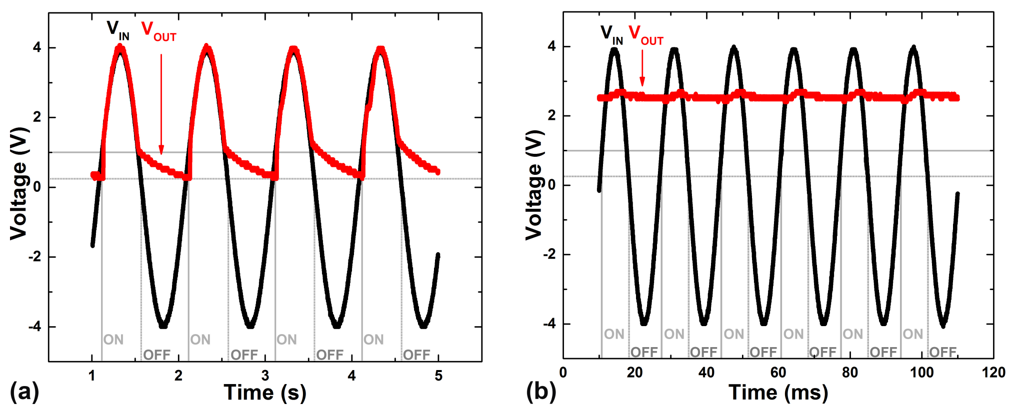


Fig. 5. Half-wave rectifier circuit with (a) p-n diode and (b) MEM relay configured as a rectifier.

The utility of a body-biased MEM relay for rectification is demonstrated using the half-wave rectifier circuit illustrated in Figure 5(b). The particular MEM relay used for this initial demonstration operates in non-pull-in mode, with V_H = 300 mV. The measured waveforms for various input ac power supply parameters are shown in Figure 6.



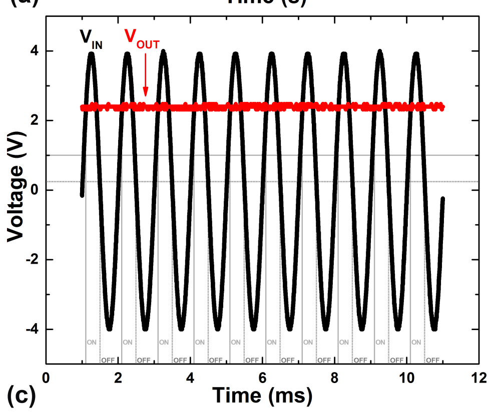


Fig. 6. Measured waveforms corresponding to (a) 1 Hz (b) 60 Hz and (c) 1 kHz input voltage waveforms for the half-wave rectifier circuit of Fig. 5(b) utilizing a MEM diode with V_{PI} = 14.0 V, V_{RL} = 13.7 V (V_H = 300 mV) and an applied body bias $V_B \approx$ -13.0 V as the rectifying device. V_{IN} = 8 V peak-to-peak; R = 660 kΩ; C = 0.33 μF. At higher frequencies, ON-state resistance limits the amount of charging of the capacitor, thereby limiting the peak output voltage of the circuit.

Because the MEM diode forward voltage is effectively lower for a reverse voltage sweep (due to hysteretic switching behavior), the diode continues to charge the load capacitor until V_{OUT} falls below $V_{IN} - (V_{RL}+V_B)$ in each cycle. Due to significant ON-state resistance (R_{ON} greater than 5 kΩ), at higher frequencies the output voltage no longer tracks the input voltage when the relay is ON, and the output voltage stabilizes at a voltage that is dependent on the frequency as well as R_{ON}.

3.2 Effect of Relay Body Bias

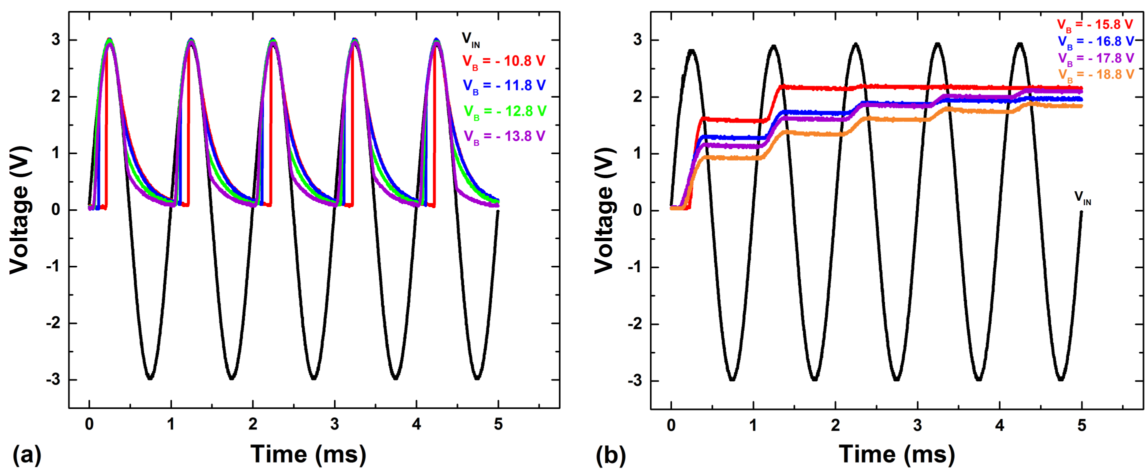


Fig. 7. Measured waveforms for (a) half-wave rectifier circuit with the load capacitor removed, utilizing a MEM diode with V_H = 200 mV, for various values of body bias voltage V_B, and (b) half-wave rectifier circuit of Fig. 5(b), for various values of V_B. V_{IN} = 6.0 V peak-to-peak; f = 1 kHz; R = 600 kΩ; C = 0.33 μF.

As shown in Section 2.3, the relay switching voltage can be adjusted by changing the value of V_B. Because V_B is applied discretely from the other circuit elements (cf. Figure 5(b)), it can be used to control the MEM diode V_F. This presents a mechanism through which the peak output of a power conversion circuit can be tuned and adjusted according to the given application. Measured rectifier outputs for a NPI-mode relay, for different values of V_B, are shown in Figure 7(a). It is evident from the output voltage waveforms that the MEM diode turns ON at a lower input voltage as the value of $|V_B|$ is increased. Although this is desirable, the relay also turns OFF at a lower voltage; therefore, in order to attain low output voltage loss for a power conversion circuit, $|V_B|$ must be set such that $V_F = V_{IN,peak}$. This is reflected in Figure 7(b), which clearly shows that larger $|V_B|$ not only causes the diode to turn ON at a lower voltage but also results in lower dc output voltage.

3.3 Discussion

As stated in the previous section, there is a fundamental tradeoff between low V_F and high V_{OUT} for the power conversion application of a MEM diode. Due to V_H, a relatively large V_F is required for very low output voltage loss in a rectifying circuit; thus, the

3-terminal MEM diode configuration is unsuitable for practical power conversion applications.

3.3.1. 2-Terminal MEM Relay Configuration

In order to have a MEM relay mimic a conventional diode, it must be configured as a 2-terminal device. That is, the body and source terminals should be tied together, as shown in Figure 8.

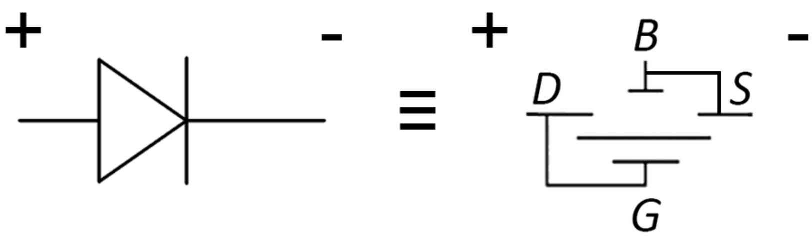


Fig. 8. MEM Diode 2-Terminal Configuration

The relay would have to be redesigned to have very low V_{PI} while retaining low V_H. Based on the simple parallel-plate capacitor model, the values of V_{PI} and V_{RL} can be calculated using the following equations [9]:

$$V_{PI} = \sqrt{\frac{8k_{eff}g^3}{27\varepsilon_0 A}} \qquad (3)$$

$$V_{RL} = \sqrt{\frac{2\left(k_{eff}g_d - F_A\right)(g - g_d)^2}{\varepsilon_0 A}} \qquad (4)$$

whereas g is the as-fabricated actuation gap thickness, g_d is the as-fabricated contact dimple gap thickness, A is the actuation area, F_A is the contact adhesive force and k_{eff} is the effective spring constant.

Because $V_{PI} \propto \sqrt{k_{eff}}$ and $V_{RL} \propto \sqrt{(k_{eff}g_d - F_A)}$, it is difficult to design a relay with both low V_{PI} and low V_H. Therefore, further design optimization is necessary for a MEM relay to operate efficiently as a 2-terminal device.

3.3.2. Effect of Relay ON-State Resistance

Another non-ideality of this MEM relay technology is high ON-state resistance, R_{ON}. Because the contacting electrodes are made of tungsten, they are susceptible to oxidation, which increases R_{ON} over the operating life of the relay [8]. At high frequencies, R_{ON}

prevents the output voltage from tracking the input voltage, as shown in Figure 9. Contact material engineering is required to overcome this performance limitation.

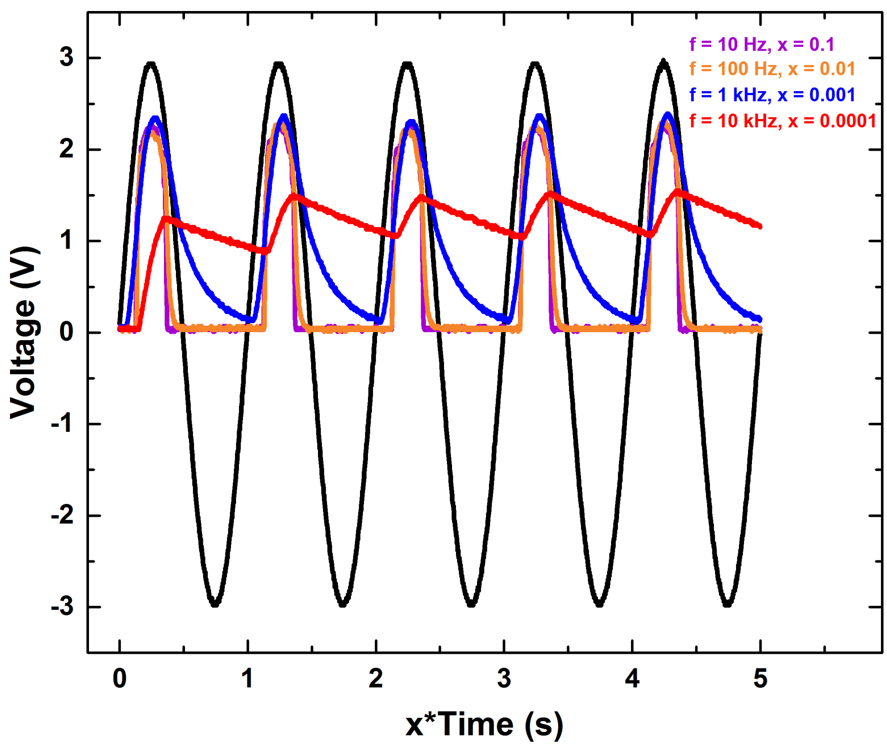


Fig. 9. Measured voltage waveforms for different values of input voltage frequency (*f*), for the half-wave rectifier circuit of Fig. 5(b). V_B = - 13.8 V. V_{IN} = 6.0 V peak-to-peak; R = 600 kΩ. The deleterious effect of R_{ON} can be seen as *f* increases.

Chapter 4. Conclusion

A MEM relay is demonstrated to be able to achieve $V_F < 300$ mV and zero I_R, so that it can potentially be used for more energy efficient power conversion than conventional semiconductor diodes. These ideal rectifying characteristics must be achieved without body biasing (*i.e.* the relay must have low native switching voltage), however, for efficient power conversion applications. Relay ON-state resistance can limit the output voltage and also should be reduced for efficient power conversion.

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