

# THE MICROMACHINED FLASHFET: A LOW-POWER, THREE-TERMINAL DEVICE FOR HIGH SPEED DETECTION OF VAPORS AT ATMOSPHERIC PRESSURE

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## ABSTRACT

This work demonstrates a three-electrode configuration for initiating microdischarges, and its application to the spectral detection of organic vapors. A strategically located high impedance gate electrode permits the microdevice to be operated with pulses less than 100 V, applied between the source and drain. The device thus consumes only 2.5  $\mu\text{J}/\text{pulse}$  at 140 Torr and 22.5  $\mu\text{J}/\text{pulse}$  at atmosphere. The microdischarge breaks down the complex organic vapors into small fragments that have characteristic emission in the UV-visible region. The operation of the flashFET as a gas sensor is evaluated by detecting acetone vapors in air ambient. The present manifestation of the device has a 1 mm x 1 mm footprint and is made with thick electroplated copper patterned on a glass substrate.

## I. INTRODUCTION

In the quest for miniaturized vapor and gas sensors, a variety of transduction methods have been explored. Chemi-resistors, chemi-capacitors, chemi-mechanical sensors, and metal oxide sensors measure changes caused by analytes to thin films [1]. However, these sensors use thin films for transduction and the properties of these films vary with process and usage conditions. Miniaturized spectral sensors can complement other sensors by not only reducing dependence on manufacturing methods but also by offering speed and specificity. Devices based on plasma and arc spectroscopy operate by exciting a gas species and observing the characteristic spectral output from the energy transitions [2]. Since all atoms emit light when excited, the technique is generic. Additionally, since each chemical species has a characteristic emission, the detection can be done in parallel, and can yet be specific. Moreover, the detection is rapid (few milliseconds) when a synchronized pulsed detection scheme is used. Miniaturized sensors based on D.C, radio frequency or microwave power and inductively coupled plasmas have been reported [3-6]. However, these devices can consume significant power and have very limited lifetime due to electrode wear. Most of these also require low operating pressures (and hence a pump) and/or an inert carrier gas like helium or argon for operation, which is a handicap for portable handheld systems. These limitations can potentially be addressed by the use of arc like pulsed discharges.

In our previous work, we have used pulsed microdischarges between two electrodes to reduce the power consumption and increase electrode lifetime. In one application, pulsed microdischarges were struck between a metal anode and liquid cathode for detecting impurities in water samples. The pulsed discharge consumed nearly 40

mJ/discharge, and was driven by a battery operated circuit. In another instance we used one-shot microdischarges between two electrodes with synchronous detection for sensing organic vapors in air ambients. This device consumed about 400  $\mu\text{J}/\text{discharge}$ . Synchronized spectroscopy enabled the use of one-shot microdischarges that reduced the power consumed further. Although this is 50x lower than other microplasma devices, there is still room for improvement. In this paper we present a three-electrode microdischarge that consumes very low power and can be triggered by much lower voltages.

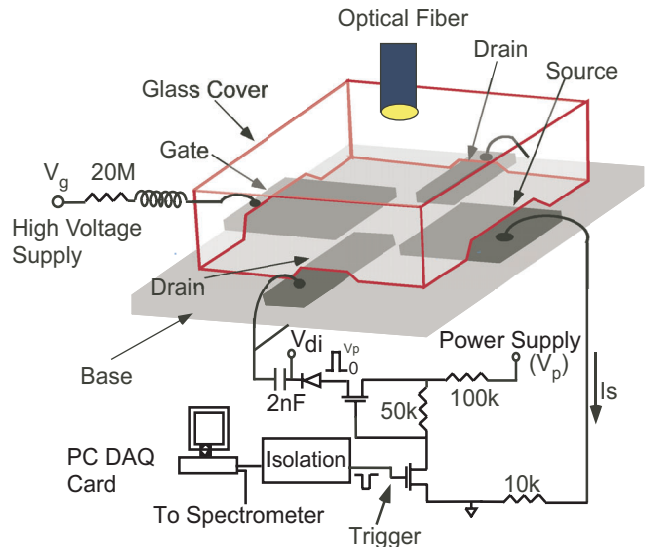


Fig. 1: Schematic of the micromachined flashFET, showing the electrode configuration, the glass cover and the discharge circuit. The gate is held at a high voltage, but the current is restrained by a 20 M $\Omega$  resistor and choke. A low voltage ( $\sim 100$  V) pulse applied to  $V_{di}$  is used to trigger the microdischarge.

## II. DEVICE CONCEPT

The flashFET (Fig. 1) is comprised of three closely spaced (electroplated Cu) electrodes on an insulating (glass) substrate. A strategically placed high impedance gate electrode maintained at a high voltage facilitates the initiation of the discharge with a relatively low voltage pulses ( $< 100$  V) between the source and drain, permitting the device to operate at a relatively low power.

Since microplasmas are driven mainly by secondary emission from the cathode [3], the source is made with a relatively large area. The drain is next to it with a typical spacing of 200  $\mu\text{m}$  and the gate is further away, spaced 450  $\mu\text{m}$  from the source. Excluding the contact pads, the device occupies a footprint of 1 mm<sup>2</sup>. The device is optionally

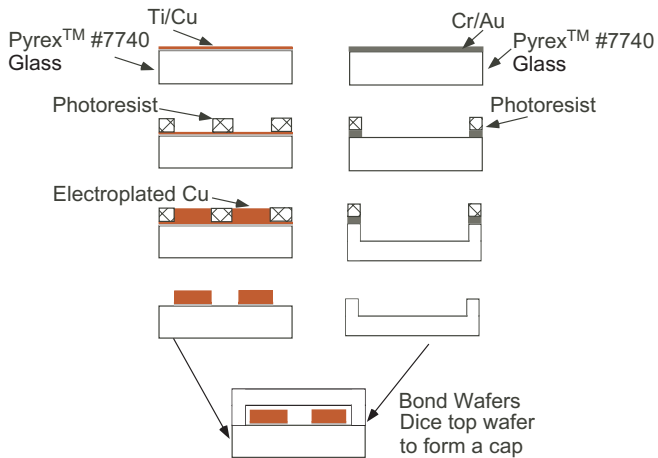
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covered with a glass dust cap that permits free exchange of vapor with the sample space.

The location of the drain ensures that the discharge current favors the drain over the gate or any other element. The drain is connected to a series capacitor. This permits the charge on it to build up to a value approaching the gate bias, which is below the breakdown voltage. The capacitor is charged up by extremely small leakage current from the gate (parasitically through the air gap and the glass surface between electrodes). A 20 M $\Omega$  resistor and an inductor are connected to the gate electrode to eliminate it as a significant current path during the discharge. This keeps the energy consumed per discharge to  $\mu$ Joules.

During testing, it is essential that no probe be connected to the drain. Even if a high impedance (20 M $\Omega$ ) probe is connected, the drain still gets pulled to ground. Then, because the drain is physically close to the gate, which is held at an elevated voltage, unintended discharges can be initiated between the gate and drain. In the absence of a probe the drain charges to the floating potential (as discussed previously) and unintended breakdown does not occur.

When a discharge is required, a relatively small pulse ( $\sim$ 100 V) from the control circuit boosts the drain above the threshold, initiating the microdischarge to the source. The current in the microdischarge decays as the capacitor is discharged.



**Fig. 2:** Fabrication process for the flashFET. **Left:** The base wafer. A 500 Å/1000 Å layer of Ti/Cu is deposited by sputtering. Photoresist (Clariant AZ 9260), 50  $\mu$ m thick, is patterned to serve as a mould for electroplating. A layer of copper, 40  $\mu$ m thick, is electroplated and the photoresist and the seed metal are etched away. **Right:** The top cap is formed by isotropically etching a cavity in glass. The cap and the base layer are bonded together.

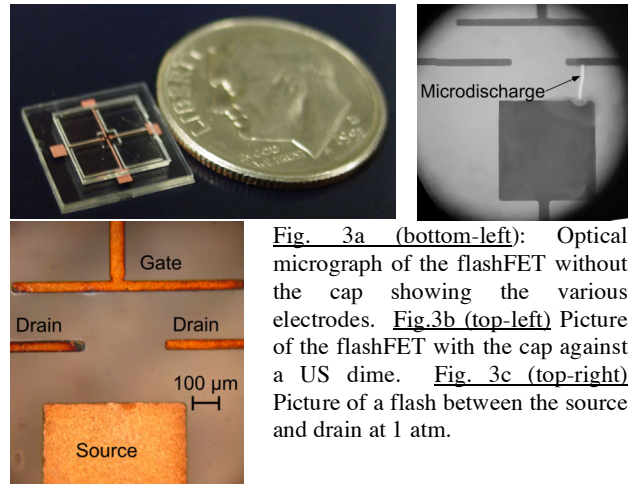
### III. FABRICATION

The fabrication process (Fig.2) starts with a blanket Ti/Cu (100 Å/500 Å) base layer sputtered on a glass substrate. The photoresist (Clariant AZ 9260) is patterned to define a 50  $\mu$ m thick mold for the plating. A layer of copper, 40  $\mu$ m thick, is then electroplated through the mold to define the electrodes. The photoresist and the base layers are then etched away to leave the flashFET structure intact.

The cap wafer is made by isotropically etching glass to a depth of 100  $\mu$ m in HF/HNO<sub>3</sub>. A layer of Cr/Au (500 Å/5000 Å thick) covered with photoresist is used as an etch mask. Finally the device and the cap wafer are diced the cap is bonded to the device by UV-curable epoxy. The device can also be packaged at wafer level by bonding the glass wafers and dicing top and bottom wafer separately.

### IV. RESULTS

Figure 3a shows a picture of the active area of the microfabricated device without the glass cap. This particular design employs a split drain. Devices with a single drain line running end to end have also been tested and show identical results. The final packaged device, shown in Fig. 3b, occupies an area of 1 cm x 1 cm. Figure 3c, shows a typical flash, which is a microdischarge between the drain and the source.

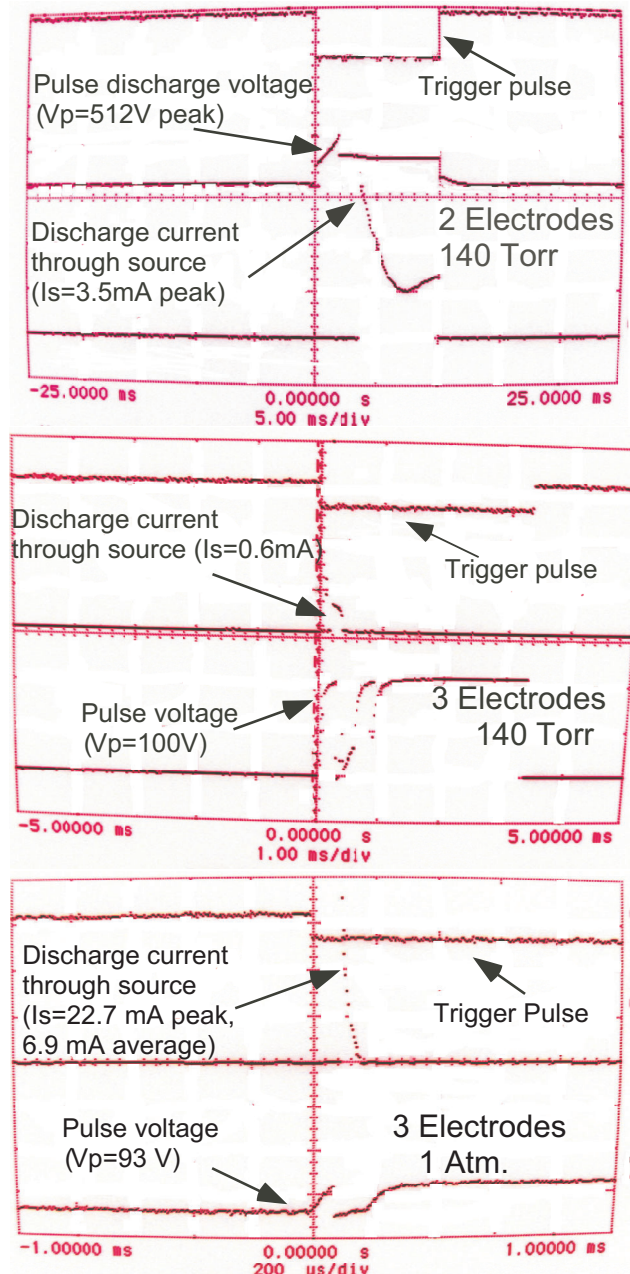


**Fig. 3a (bottom-left):** Optical micrograph of the flashFET without the cap showing the various electrodes. **Fig.3b (top-left)** Picture of the flashFET with the cap against a US dime. **Fig. 3c (top-right)** Picture of a flash between the source and drain at 1 atm.

Figure 4a shows the oscilloscope waveforms for a two-electrode pulsed microdischarge between the drain and the source at 140 Torr. At the top is the trigger signal. In the center is the voltage waveform at the drain, observed through a 100:1 voltage divider. At the bottom is the current through the source measured by the voltage across a 10 K $\Omega$  resistor connected to the source. We had employed such a discharge in our earlier work [8]. At these pressures the discharge takes the form of plasma confined to the cathode. As shown in the figure, the breakdown voltage was 515 V. The peak current was 3.5 mA and the energy dissipated in one cycle was 3.5 mJ. Note that the capacitor did not discharge all the way and the voltage was maintained at a slightly lower sustain voltage and current throughout the duration of the trigger.

Figure 4b shows the oscilloscope trace for a flashFET microdischarge at the same pressure as in Fig. 4a, for comparison, with the gate was held at 800 V. The center waveform is the current signal, and the waveform at the bottom is the signal at  $V_{di}$ . The drain cannot be probed directly for reasons explained in section II. The energy consumed was calculated by summing the output of both power supplies for  $V_g$  and  $V_{di}$  over the duration of the cycle. The flashFET consumes 2.4  $\mu$ J/cycle at 140 Torr, which is a

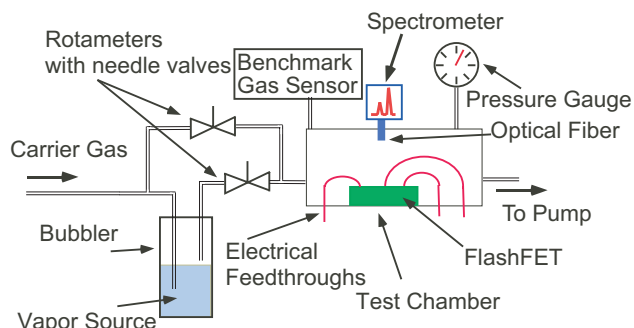
1000x reduction over the two-electrode configuration. The device still forms a plasma glow over the cathode, but unlike the two-electrode microdischarge, lasts for a short duration ( $\sim 200 \mu\text{s}$ ). This factor alone helps reduce the power consumed by 50x. Between the source and drain, a much lower voltage (100 V) is needed to trigger the discharge with a three-electrode configuration. The voltage at  $V_{di}$  goes to ground, which implies that in the case of a flashFET discharge, the capacitor discharges completely.



**Fig. 4a (top):** Waveforms showing the formation of a two electrode pulsed microdischarge in air at 140 Torr. **Fig. 4b (center):** Waveforms showing the flashFET microdischarge at 140 Torr with  $V_g=800$  V. The power per cycle is calculated by summing the output of the two power supplies. This discharge consumes  $2.5 \mu\text{J}/\text{cycle}$ . **Fig. 4c (bottom)** Waveforms showing the flashFET microdischarge at atmosphere, with  $V_g=1000$  V. The device consumed  $22.5 \mu\text{J}/\text{cycle}$ .

Figure 4c describes the flashFET microdischarge at 1 atm., the desired use condition. The gate was held a 1000 V. The trigger voltage was 93 V, and the peak current was  $22.7 \mu\text{A}$ . Note that the timescale on the trace is smaller than in Fig. 4a and Fig. 4b, as the microdischarge at atmosphere is driven by large currents lasting for a short duration. In this case, the energy consumed was  $22.5 \mu\text{J}/\text{cycle}$ . This is 100x smaller than a two-electrode microplasma at 140 Torr.

For evaluating the use of the flashFET as a organic vapor sensor, it is placed in a chamber with a constant vapor concentration. A schematic of the setup shown in Fig. 5. Before the experiment, a vacuum pump is used to evacuate the test chamber to flush out vapors already present in the chamber. Vapor laden carrier gas (nitrogen) is flowed through and a dynamic equilibrium ensures that a constant vapor concentration is maintained inside the chamber. Changing the flow rate of the carrier gas through the bubbler (which contains the liquid) varies the vapor concentration. A commercial VOC sensor (MiniRAE 2000 from RAE Systems), is used to provide a benchmark measurement. Spectroscopy is performed by coupling the emitted light from the microdischarge to a palmtop spectrometer, (USB2000 from Ocean Optics Corp.) The spectrometer integrates the signal for 10 ms and is triggered in synchronism with the discharge trigger. A long integration time is used as it captures not only the glow, but also the afterglow of the discharge, which is known to have significant spectral information [3]. The optical spectrum of the microdischarge in air at 1 atm., without the glass cap is shown in Fig. 6. As expected, lines corresponding to nitrogen are prominent in the discharge.



**Fig. 5:** Test set-up for sensor. Vapor concentration is varied by flow rate of carrier gas through a bubbler containing the compound of interest. A commercial vapor sensor (MiniRAE 2000 from RAE Systems) provides a benchmark measurement. The optical signal is observed through a fiber optic cable, connected to a palmtop spectrometer.

Figure 7 shows the air spectra with the glass cap. The lines in the UV region are seen to be attenuated by the Pyrex™ cap, while the visible portion of the spectra does not vary much. This is expected as the transmittance curve for Pyrex™ (Fig. 8) shows a dip at 300 nm.

The microdischarge spectra of acetone vapor at a concentration of 320 ppm are shown in Fig. 9. Lines corresponding to carbon-containing fragments like  $\text{C}_2$  and CH can clearly be identified. By measuring the relative

intensity of these lines, it is possible not only to detect a compound, but also to identify the constituent elements of an unknown compound.

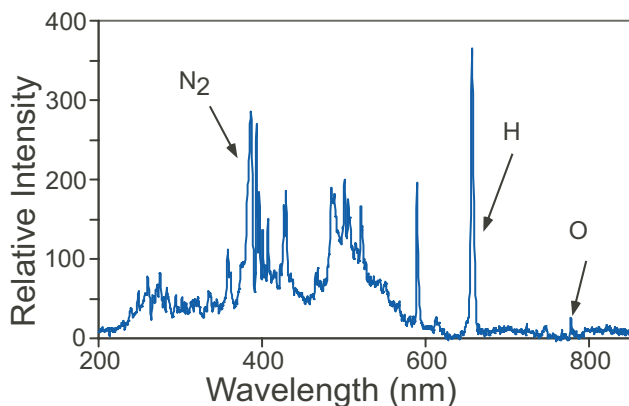


Fig. 6: Spectra of the flashFET discharge in air at 1 atm. Lines corresponding to nitrogen and water vapor dominate.

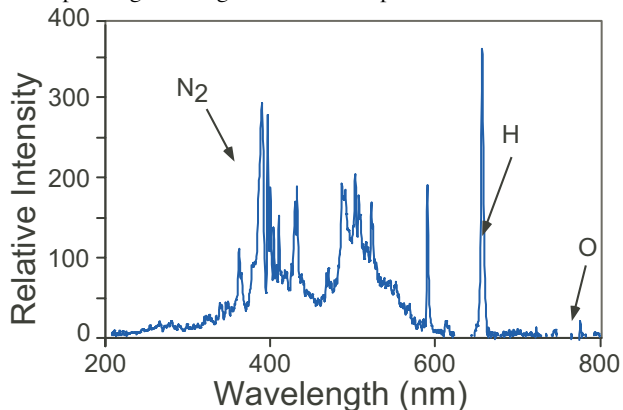


Fig. 7: Spectra of the microdischarge in air with the Pyrex™ cap on. Compared to Fig. 6, the UV portion of the spectra is attenuated but the visible region remains same.

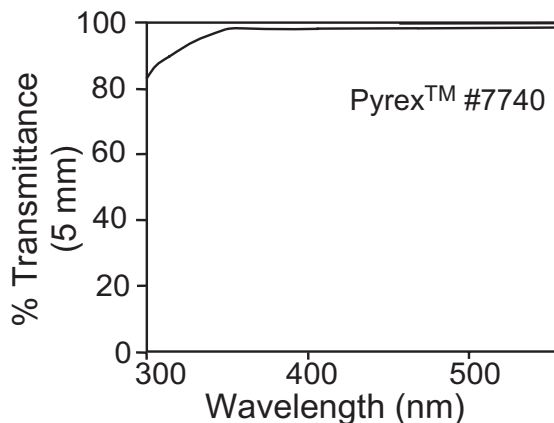


Fig. 8: Transmittance curve for Pyrex™ #7740 glass.

## V. CONCLUSION

This effort successfully demonstrates a low power three-electrode microdischarge. The three-electrode configuration employs separate high voltage and high current electrodes, thereby reducing the energy per discharge to the  $\mu\text{J}$  regime. Despite the lower power consumption, no loss in spectral resolution is seen. The

device easily detects low concentrations of acetone in ambient air, which is comparable to results from other microdischarges. Additionally since this technique works at atmospheric pressure, it greatly reduces the need for pumping and specialized packaging. Together these features make the flashFET appealing for miniaturized sensors.

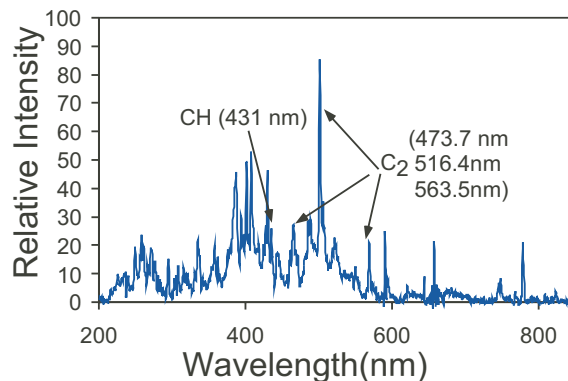


Fig. 9: Spectra of the microdischarge in 320 ppm acetone with air (at atmos.) as the carrier gas. Lines corresponding to fragments of carbon compounds are clearly evident.

## ACKNOWLEDGEMENTS

This work is funded in part by funding from the National Science Foundation. The authors would like to thank Mr. Weibin Zhu for help with the fabrication.

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