Characterization and applications of discrete memristor

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***Abstract*—In the present paper, we study the electrical properties of cat's whisker, subset of a larger class of devices called coherer, which were recently proposed to be a canonical implementation of memristor. The devices memristive properties were found to be dependent on the contact area and pressure. The maximum current flown through the device is found to be the controlling state-variable. By controlling the state-variable, we found that the device can be programmed into multiple resistance states and can be reset to higher resistance state, which has immediate application in programmable analog circuits. We have demonstrated that by using programming current wave, we can achieve programming of properties such as threshold voltage, amplifiers gain and duty cycle.**

I. Introduction

Memristors are passive non-linear resistive elements whose resistance is dependent on the history of the system. The functional properties of the memristor was first proposed by Leon O.Chua in 1971 [2] showing the existence of new passive two terminal device in class of memory circuit elements.

The realization of the memristor came in 2008 when HP announced the first nanoscale memristor [9]. It was discovered in the form of a partially doped titanium dioxide on nanoscale thin film with platinum electrodes [10].

Since its realization in 2008, recent interest has been driven by the realization that memristors are likely to have a significant impact in electronic circuit design both in digital and analog circuits [5], [7]. Recent work shows that it has an application in non-volatile memory storage and also offers advanced analog functionalities. The memristor is also proposed to be electrical equivalent of a synapse and hence is believed to play an important role in neuromorphic computing and learning [6].

The application of memristive circuits and the availability of memristors in nanoscale, has sparked the need for a discrete component for fast prototyping.

Recently Gaurav et.al [3], [4] have shown the canonical implementation of a memristor consists of devices having imperfect metal-metal contact as in coherer or metal-semiconductor point contact as in cat's whisker detector(also called crystal detector).

In case of bipolar input, these devices form a pinched hystersis loop, which is a fingerprint for memristive devices. Though these devices show memristive behaviour and some other interesting phenomena, it is highly sensitive to the point of contact and the pressure applied.

In the present paper we discuss about the experimental results on electrical characteristics of this discrete memristor and an approach to use it in programmable analog circuits. Applications such as programmable gain amplifier, programmable threshold comparator, programmable switching thresholds Schmitt trigger have been implemented and experimental results are presented.

This paper is organized as follows. Section II of this paper discusses the electrical properties of cat's whisker and describe the experimental setup we used to perform experiments.In section III we demonstrate applications of this memristor in analog circuits and conclude in section IV.

II. Discrete Memristor

The discrete memristor studied in this paper comprises of a metal-semiconductor point contact based device called as cat's whisker detector. This device was earlier used in radio wave detector due to its diode-like rectifying properties [1][8].

The device was found to be state-dependent resistor where the state variable governing it, is found to be the maximum current that has passed through the device I_{max} [3].

We found that the device is highly sensitive to the pressure applied and the point of contact and the nature of the I-V curve changes depending on these two factors.

To provide current mode input an experimental setup was used, discussed next. A detailed analysis of class of devices called coherer can be found in [3],[4].

A. Experimental Setup

Flow diagram for operation of experimental setup is shown in Figure 1. The core circuit of the setup was designed using commercially available components. The main components installed in the current board include AD844 (current feedback operational amplifiers), MCP4725 (12-Bit I2C Digital to Analog Converter),AD620 (Instrumentation Amplifier IC). AD620AN is a low Drift, low power Instrumentation Amplifier with set gains of 1 to 10000.

In our experimental setup, we provided current mode input to the device and measured the output voltage across it. To supply the current waveform, Current feedback operational amplifier is used. AD844 AN is 60MHz, 2000 V/s Monolithic Op Amp is used for voltage to current conversion.

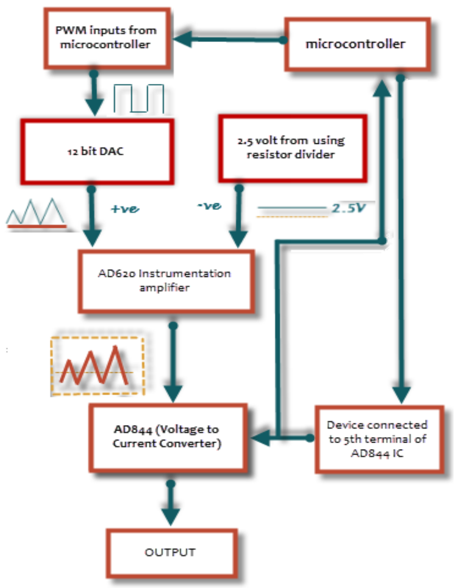

Fig. 1. **Working flow diagram of breakout board**

B. Experimental Results

For cat's whisker detector setup, memristive behaviour repeats within the same range of resistances for the same spot of cat's whisker and its properties are dependent on the spot where cat's whisker touches the crystal.

It was found that the nature of I-V curves such as the non-linearity, resistance range, threshold voltage (V_{th}) is found to be dependent on the area, location and the pressure applied.

The device transient electrical characteristics are studied by measuring voltage across the device when current as input is provided.

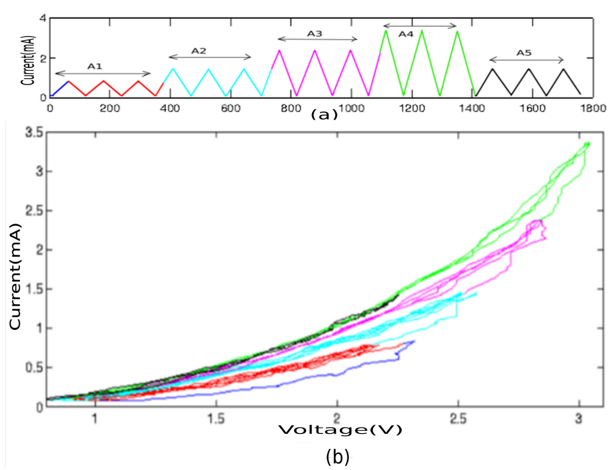

Fig. 2. a) Current wave input to device. b) Plot showing I_{max} behaviour.

1) Imax behaviour: For the analysis of the Imax behaviour, input current waveform as shown in Figure 2(a) is provided. The corresponding transient output voltage is measured. The triangle current waveforms are of peak sequence 1mA, 1.5mA, 2.5mA, 3mA and 1.5mA in Figure 2(a).

The resultant I-V curve obtained is as shown in Figure 2(b). The resistance decreases with every input current pulse of higher peak value but remained essentially non-linear. It is further observed that the resistance value adjusts such that maximum voltage across device remains around the threshold voltage V_{th}. The V_{th} over many samples is found to be dependent on the spot and the pressure of cat's whisker on the crystal.

The device retraces the previous I-V curve when smaller amplitude current peak is provided and hence can be used to read the previous resistance.

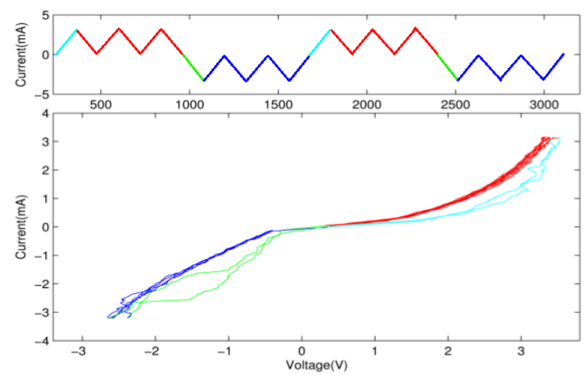

Fig. 3. Plot showing reset behaviour

2) Bipolar memristive charactersticss: For the analysis of bipolar memristive charactersticss of the discrete memristor, input current waveform as shown in Figure 3 is supplied. The current peaks are of amplitude +-3mA. The corresponding transient output voltage is measured.

As seen from the Figure 3, the device resistance gets adjusted to one state in positive direction and another state in negative direction. It traces these fixed resistances in both direction, when switched from positive to negative and vice versa and hence shows a pinched hysteresis loop.

The device gets programmed in each direction by a large positive/negative input peak current and remains in the same resistance state when provided with a smaller input current. It switches its resistance when provided with a large input current peak in opposite direction. Hence the device can be used in resistive memory, in which large pulses write information and small pulses can be used to read information and to reset the data, a large negative pulse is given.

III. Programmable Analog Circuits

Based on the detailed electrical analysis in section II, we find that -

1) Device can be programmed by high amplitude current pulses and low amplitude current pulses can be used in analog operation.

2) Each programming current pulse changes the resistance by a discrete amount.

With the above properties, device can be used in number of analog circuits. Some of them are shown here.

A. Programmable gain amplifier

We start by demonstrating programmable amplifier based on discrete memristor. The schematic of this circuit is as shown in Figure 4.

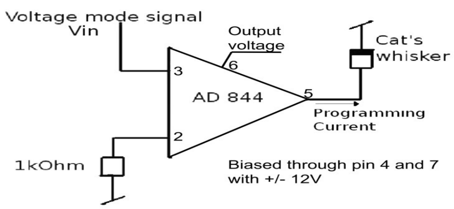

Fig. 4. Schematics of a programmable gain amplifier

The programming current I is given by $I = V_{in}/R$ and the output voltage V_{out} is given by $V_{out} = I * M(r)$, where M(r) is the device resistance and $R = 1k\Omega$.
Hence the ratio of output to input voltage is given by-

$$V_{out}/V_{in} = M(r)/R \tag{1}$$

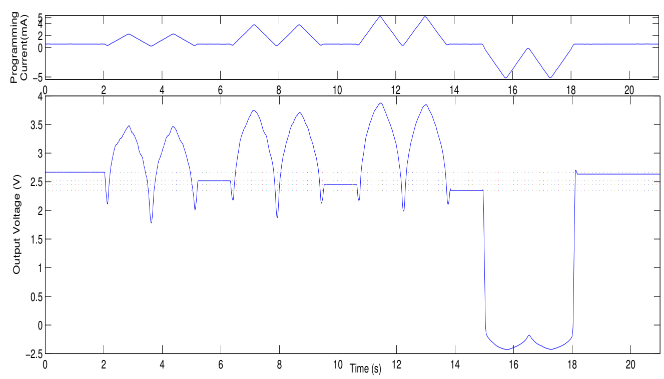

Fig. 5. In these measurements, voltage V_{in} is kept constant to 0.5V in analog operation. Programming current consists of 2mA, 4mA and 5mA triangle pulses.

Experimental results are as shown in Figure 5. Amplifier's gain is controlled using triangular current pulses. As shown in figure the output voltage decreases when the device is programmed with 2mA, 4mA and 5mA triangle current peaks. Gain is observed to decrease in each case when input voltage V_{in} is kept constant to 0.5V. Gain increases to original value when negative current peak is provided which resets the device resistance. The gain of the circuit changes by 11.7%.

B. Programmable threshold comparator

The next circuit we consider is programmable threshold comparator whose schematics is as shown in Figure 6. Voltage

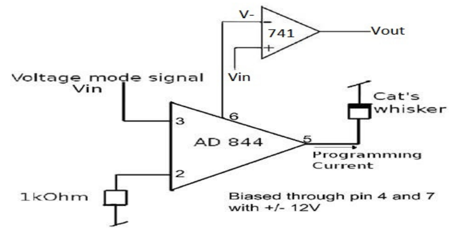

Fig. 6. Schematics of a programmable threshold comparator

obtained at negative terminal of Operational amplifier is

$$V_{-} = V_a M(r)/R \tag{2}$$

where V_a is the voltage mode signal, M(r) is the resistance of device and $R = 1k\Omega$.
A sinusoidal wave $V_{in} = 3sin(2\pi ft)$ is input to positive terminal of operational amplifier with f = 1Hz.
Experimental results are as shown in Figure 7. Threshold voltage V_{-} is controlled using programming current. When programmed by a 5mA current peak, the resistance M(r) decreases by 670Ω, thereby reducing the threshold voltage. Due to decrease of threshold voltage, we obtain a wider output pulse starting from t=7s.

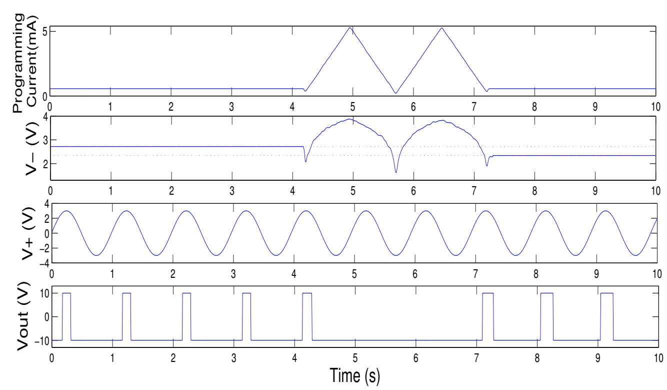

Fig. 7. Threshold voltage V_{-} is controlled using programming voltage. 5mA current peak reduces the resistance by 670Ω and decreases the threshold voltage. Output voltage of comparator is Vcc when $V_{+} > V_{-}$, else its -Vcc. Here Vcc=+-10V.

C. Programmable switching thresholds Schmitt trigger

Schematics of programmable switching thresholds Schmitt trigger is as shown in Figure 8. Schmitt trigger is a comparator circuit with positive feedback. The two switching thresholds are given by

$$\frac{\pm V_{cc}R2 + V_W R1}{R1 + R2} \tag{3}$$

where $V_{cc} = 10V$, $R1 = 1k\Omega$ and $R2 = 100\Omega$. The voltage V_W is controlled using programming current pulses as seen in Figure 9.
A sinusoidal wave $V_{in} = 4sin(2\pi ft)$ is input to negative terminal of operational amplifier with f = 1Hz.
Programming current wave is same as shown in Figure 5. Programming pulses decrease the resistance and hence the voltage

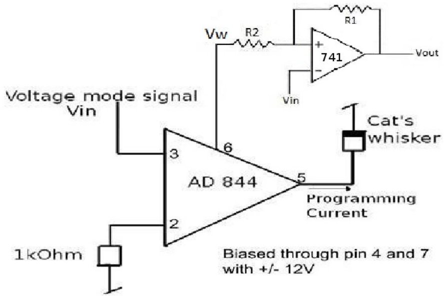

Fig. 8. Schematics of a programmable switching thresholds Schmitt trigger

at V_W decreases. With decrease of Voltage V_W the threshold decreases in both direction i.e. positive threshold magnitude decreases and negative threshold magnitude increases. As a result, the output voltage V_{out} occurs at different values of V_{in}.

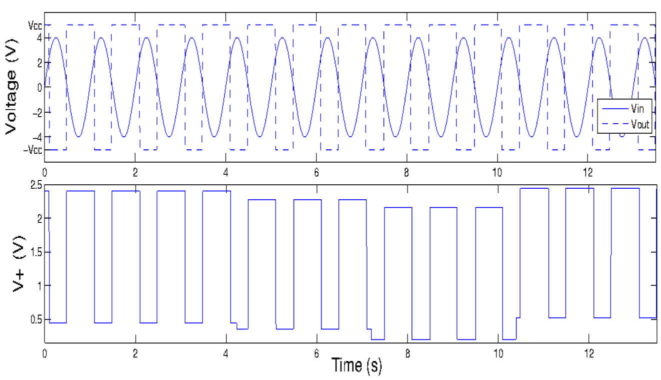

Fig. 9. Programmable switching threshold output response with input voltage $V_{in} = 4sin(2\pi ft)$ with f=1Hz, and V_+ varying due to programming pulses. The figure also shows the reset effect which resets the threshold to its original value.

IV. Conclusion

The behaviour of the metal-semiconductor point contact(cats whisker device) memristor is discussed. We have observed that the device's electrical characteristics depend upon the area, pressure and location of cats whisker and the nature of I-V curves changes accordingly.

By controlling the state-variable, we found that the device shows two types of behaviour, Imax and Reset. Observations over large number of samples show that the device can be programmed into multiple resistance ranges by different large amplitude current peaks and device state can be read by small current peaks.

It is observed that the I-V behaviour in bipolar current mode input is asymmetric and with large negative current peak the device reset to a higher resistance state. Small positive current can be used to read the higher resistance state.

Since the device resistance state was found to be a a function of I_{max}, it has usage in applications involving multiple resistance states including multi-bit storage, programmable amplifier etc.

Analog circuits have earlier been implemented in [7], but using a memristor emulator. We have demonstrated the operation and experimental data of these programmable analog circuits using discrete memristor. By using programming current wave, we have achieved programming of properties such as threshold voltage, amplifier's gain, duty cycle.

We have thus shown that by controlling the state-variable of cats whisker detector, or class of devices called coherers, we can achieve useful analog circuits.

V. Acknowledgement

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