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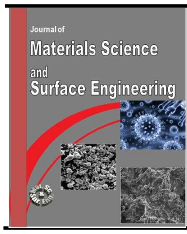

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Low Temperature Electrical Characterization of A Semiconductor Bridge Igniter

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Abstract

A semiconductor bridge (SCB) igniter used to ignite energetic powders such as pyrotechnics, propellants, and explosives typically require a tenth of the energy input as compared to a bridge wire with the same current and is capable of igniting in tens of microseconds. Hence, it has become a popular choice of an electro-explosive device in commercial and military applications. Testing the performance and suitability of these devices in snow filled terrains and low temperature environment becomes essential in view of these applications. In this paper, we present our studies on a SCB igniter, where its electrical properties were studied over a wide range of temperature and frequency using complex impedance spectroscopy (CIS). Our results show that the resistance of a 3.2 Ω device increases by 25% as temperature decreases from 300 to 70K. Also, for any temperature the impedance remains constant up to 5 orders in frequency beyond which the inductive reactance increases. In addition the time required to fire the device is increased marginally at 77K when compared with room temperature showing that the SCB igniter can be used effectively in cold environments.

Introduction

Electro-explosive devices (EEDs) convert electrical energy into explosive energy in order to produce detonation output. Semiconductor bridge (SCB) igniters are cutting-edge electro-explosive devices which are reliable and safe compared to conventional hot-bridge wires [1]. The low firing energy, fast function times, low no-fire currents, less weight, small volume and low cost makes an SCB igniter more advantageous than hot-bridge wires. In addition, SCB igniters are unaffected by exposure to harsh electro-magnetic interference (EMI) environments and are insensitive to electrostatic discharge (ED) and radio frequency (RF) hazards. [2-7]. These features make it desirable for many military applications and it is being effectively used with various devices such as pin pullers, piston actuators, wing deployment devices, actuators, rocket motors, cutters, explosive bolts etc. It is also successfully been used in oilfields where the EED needs to be insensitive to common electrical hazards encountered around well sites [8].

The semiconductor bridge has less mass than a hot bridge wire which results in significantly reduced function time [9,10]. The semiconductor bridge used in the igniter is a thin film bridge whose thickness is about several microns, which makes its thermal capacity small leading to its high-speed response [11,12]. A current pulse across an SCB produces a hot plasma which efficiently ignites the explosive pressed against the SCB. Heat transfer is a micro convective process. When the SCB bursts into the plasma, the plasma percolates up into the powder, and condenses onto the explosive particles heating them to their ignition temperature [2]. The SCB is made of semiconducting Si which is highly doped with phosphorus to an approximate concentration of 10^{19} to 10^{20} atoms/cc which decreases the resistivity substantially. Finally, the device is patterned to obtain a bridge with a resistance of a few ohms [13].

In view of the military applications of the SCB igniters, it becomes important to test its performance and suitability at low temperatures present on snowy terrains and glaciers. Recently, the Armament Research and Development Establishment (ARDE) of India have effectively developed SCB igniters of various size which have gone through series of military standard and qualification tests such as thermal shock test, tropical exposure test, bump & jolt test, drop test, rain test, vibration test, salt spray test, acceleration test, etc. In this paper, we report on the detailed structural and surface characterization of these devices using x-ray diffraction (XRD) and x-ray photo-electron spectroscopy (XPS). Furthermore, we present the electrical characterization of these devices at low temperatures (50-300 K) using complex impedance spectroscopy. We also measured the response time for firing at 77K which showed a marginal increase from its value at room temperature at the same current. Our results show very small change in the electrical properties at low temperature which makes it suitable for low temperature applications. Study of mechanical properties using nanoindentation technique and survey scan of SCB surface has been reported earlier [14].

Experimental

Materials and methods

A typical SCB device is fabricated by the state-of-the-art semiconductor fabrication technology. It consist of an H shaped highly doped polycrystalline Si (poly-Si) layer deposited over a layer of SiO_2 which is grown on a Si wafer. Al pads are deposited over the outer two legs of the H shaped poly-Si film and these two pads form the bridge. The length of the bridge determined by the spacing of the Al pads is 100 µm. Typically the doped polysilicon layer is 2 µm thick and the bridge is 380 µm wide. The H shaped polysilicon layer is highly doped (~10^{20} cm^{-3}) with phosphorus impurities to achieve few Ω bridge resistances. The Al pads provide a low ohmic contact to the underlying doped layer. The

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insulating layer of SiO_2 enables the heat to concentrate on the bridge when the SCB device is functioning [15]. The top view and cross sectional view of SCB surface are shown in figures 1(a) and 1(b) respectively. Two devices are fabricated on a single chip forming a dual chip SCB device. Many such dual chip SCB devices of comparable bridge resistance were used for the current study.

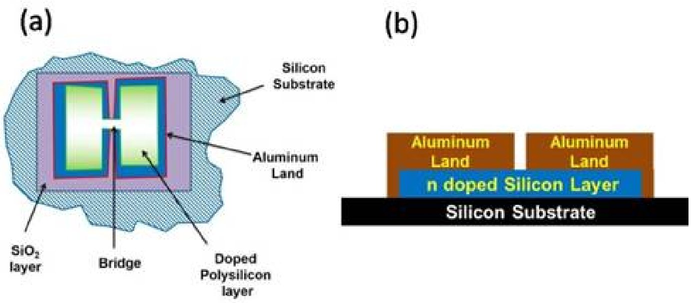

Figure 1: (a) Top view of SCB device and 1(b) cross sectional view of SCB device.

The devices were further structurally characterized by X-ray diffraction (XRD) using a 40kV and 1.6 kW Ultima IVX-ray diffractometer with a mono-chromatized X-ray beam of Cu-K_α (λ = 1.541 Å). X-ray photoelectron spectroscopy was employed to determine chemical state information of the SCB surface and the spectra were obtained from a PHI 5000 Versa Probe. The SCB device were mounted on the sample holder using double-sided adhesive tape and placed into the vacuum chamber at a pressure of 1.3 X 10^{-7} torr. XPS was performed using the aluminum K-α x-ray source (1486.6eV) at 50 watts. Narrow scan (pass energy of 23eV) were performed on the Al2p, Si2p, O1s and P2p peak. The step size for the narrow scan was 0.1eV with a dwell time of around 20 msec. Before the XPS measurement each layer was sputtered by Ar^{2+}ions for 2 minutes in order to obtain a clean surface.

The DC transport on one of the SCB device of a dual chip was carried out from 300 -70 K in a sample in vacuum low temperature closed cycle cryostat in a two probe configuration using a Keithley 2400 source meter. The measurement was done at 1 mA which was much lower than the all-fire current for the given device. In order to measure the frequency dependence of the resistance of the device, the impedance of the SCB device was measured from 20 Hz to 2 MHz with the Agilent E4980A LCR meter also using a two probe configuration at different temperatures between 300-50K. The time required for a SCB to fire at a constant current (also called the all fire current test, AFC) was conducted using the circuit shown in Figure 2.

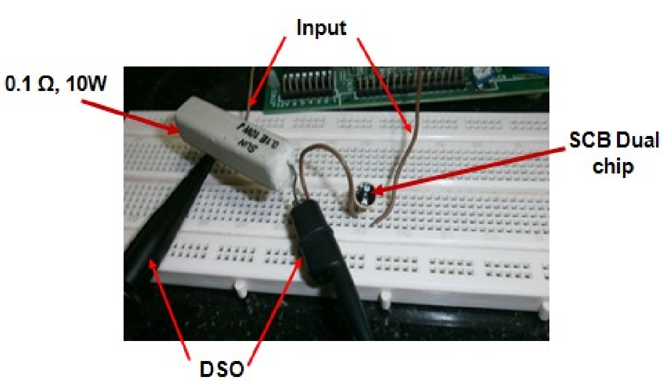

Figure 2: Circuit for all fire test

A constant current was applied to a series combination of a 0.1 ohm, 10 W resistor and the SCB. The current across the SCB was recorded on a digital oscilloscope (DSO) which gave the time for firing of the SCB. This experiment was done both at room temperature and at 77K. For the experiment at low temperature, the device was immersed in a bath of liquid nitrogen. The AFC test was done on various devices with similar impedance to check the dependence of the firing time on the current at room temperature.

Results and Discussion

Surface and structural characterization of SCB devices

The XRD pattern of the SCB device is shown in Figure 3(a). All peaks can be indexed to either Si or Al coming from the poly-Si layer and the Al contact pads. No characteristic impurities were observed, indicating that the SCB device was in pure phase. Furthermore, the chemical state of the Al, phosphorus doped poly-Si and the insulating SiO_2 present in the SCB devices shown in Figure 3(b) from the narrow scan XPS spectra of Al2p, Si2p, O1s and P2p for the SCB chip surface. These spectra are used to find out the chemical composition of both film surfaces based on the integrated area under the assigned element peak and the sensitivity factor of the element. [9] [16]. XPS spectra showing the P2p spectra revealed the presence of elemental phosphorus.

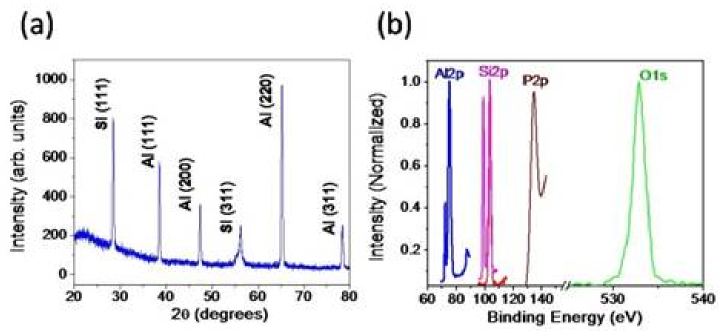

Figure 3: (a): XRD pattern of the SCB device, and (b): XPS of the SCB device.

Electrical properties of the SCB devices

DC resistance of the SCB device decreases linearly with decrease in temperature (See Figure 4(a)) indicating that the device shows metallic behavior arising from the high doping of the semiconductor. The real (resistance) and imaginary (reactance) part of the impedance for temperatures ranging between 50K to 300K are plotted in Figures 4(b) and 4(c) respectively. As seen from figures4(b)-(c), at all temperatures, the real part as well as the imaginary part of the impedance does not vary with frequency as it is swept through 5 orders of magnitude. Only beyond 10^5 Hz changes in impedance of the SCB device is observed as the inductance increases substantially at very high frequencies. This proves the robustness of the electrical properties of the SCB devices at low temperatures and high frequencies.

Another important parameter for the SCB devices is the response time required for firing. The AFC test, where the response time is measured for different constant currents (higher than the no fire current, NFC) for different devices with comparable impedances was carried out. Figure 5(a) shows the result of the AFC test done at room temperature at different constant currents. It is clear that as the current increases the time required for the device (tested with different devices of comparable impedances) to fire reduces. However, the response time to firing of the SCB devices needs to be verified at low temperatures before concluding about its applicability in cold environments. To ascertain that, we measured the time required to fire for two similar bridges of a dual chip SCB device with ~1 ohm impedance at 300 K and 77 K. Figure 5(b) shows the DSO output for the AFC test done at room temperature while Figure 5(c) is the DSO output of the corresponding test done at liquid nitrogen temperature (77K). It is clear that at 3A firing current, the response time of the device marginally increases from 1 sec to 4 sec. For lower currents, the response time at low temperatures will be faster making it suitable for use in cold environments.

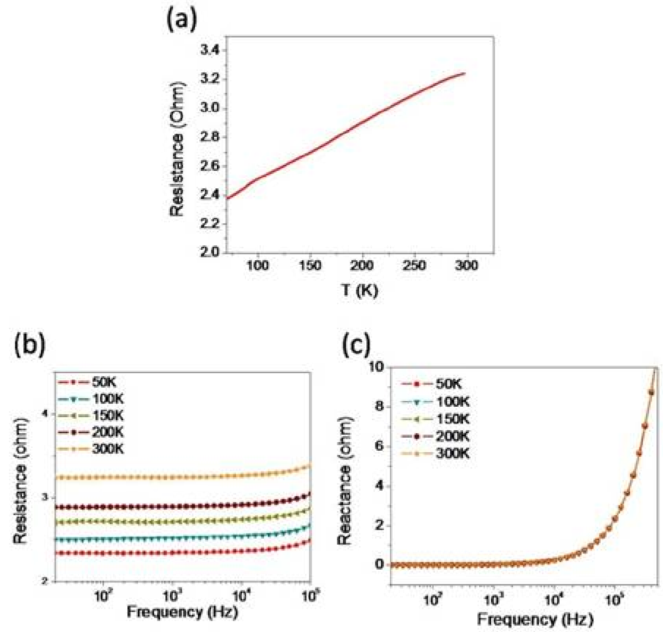

Figure 4: (a) Temperature variation of resistance of an SCB device (b) Frequency variation of resistance for the SCB device at different temperatures from 300 – 50 K and (c) Frequency variation of reactance for the SCB device at different temperatures from 300 – 50 K.

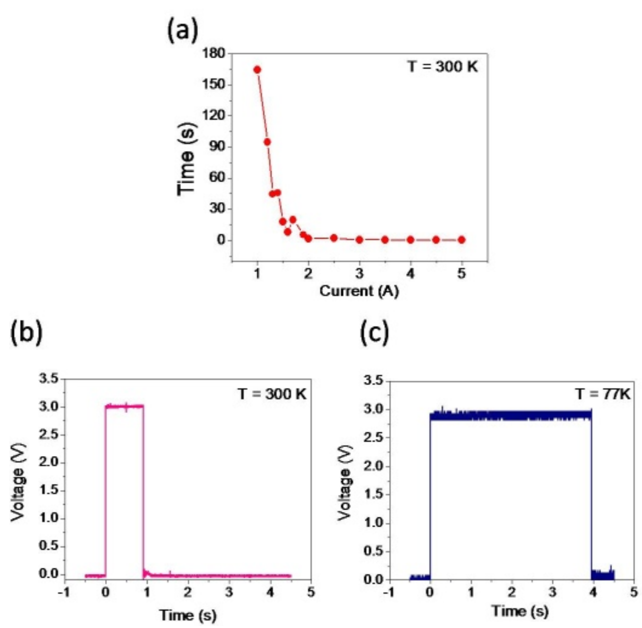

Figure 5: (a) Firing time of SCB devices with same impedance for different currents tested at 300K, (b) DSO waveform of the all fire test of a SCB device of ~1 ohm impedance at 300 K with 3 A current and (c) DSO waveform of the all fire test of a SCB device of ~1 ohm impedance at 77 K with 3 A current.

Conclusions

We report the low temperature and high frequency electrical properties of well characterized SCB devices having room temperature impedance of the order of a few ohms (1-4 ohms). The DC resistance of the bridge increases with increase in temperature and essentially behaves as a degenerate semiconductor due to the high amount of n-doping in the device. The real and imaginary part of the impedance does not change appreciably as the frequency is changed by 5 orders of magnitude. Beyond 0.1MHz, the inductances contribute to increased impedances of the device. Most importantly, the response time of the devices to firing increases marginally at 77K. Our results clearly depict that the electrical properties of the SCB devices does not change with temperature and frequency and is suited for efficient operation in cryogenic environments.

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