Development of Semiconductor Bridge Igniter

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Abstracts

We have developed a polysilicon semiconductor bridge (SCB) igniter which produces a plasma discharge that ignites explosive materials pressed against the bridge. Our experiments have demonstrated that the SCB produces a hot plasma that ignites explosives, when driven with a short, low energy peak. The SCB, a heavily-doped film, typically 100 μm long by 300 μm wide 5 μm thick, is 30 times smaller in volume than a conventional bridge. We described the SCB operation and processing, and the requirement of obtaining a plasma discharge in order to ignite the explosive material.

1. Introduction

Electro-explosive devices fall into one of two basic groups(1). The first group is electro-thermally initiated devices which respond to relatively low electrical energies. The second group is electro-shock initiated devices which include exploding wire and foil designs requiring very high energy levels. The shock initiated devices have the advantages of fast and repeatable function times. The shock initiated devices also exhibit a very high resistance to inadvertant initiation. However, high initiation energies and power levels are normally required which lead to larger and more expensive electrical firing systems. The electro-thermally initiated group have not matched the inherent input safety characteristics or response time of the shock-initiated devices. Typical response times for the thermally-initiated devices range from about 5 microseconds to several milliseconds, while the shock-initiated electro -explosive devices respond in less than 1 microsecond. However, shock-initiated devices typically require larger and more expensive firing circuits for initiation because they use higher electrical voltages and dissipate to higher power levels.

Most electro explosive devices (EED) are initiated with a metallic bridgewire(2) that is electrically heated as a firing current passes through the bridgewire. Typically, a 3 to 5 amperes current is passed through the wire heating it to approximately 900K, the hot-wire conductively heats the powder pressed against it, igniting the powder and producing a slow burn or deflagration in the powder column. For these hot-wire devices a usable explosive output is usually not obtained until several milliseconds after the current pulse is applied. Hot-wires are used in igniters, actuators, matches, squibs and detonators. If the device is exposed to potentially hazardous electromagnetic radiation that could heat the bridge inadvertently, then the bridgewire's thermal and electrical impedance can be lowered so more electrical current is required to initiate the explosive materials.

The use of silicon as a substitute for the metallic bridgewire(3) presents several potential advantages and additional design challenges. Silicon is different from metal bridgewires, when heated electrically, silicon forms a high temperature plasma which becomes very conductive and rapidly converts the electrical energy into heat. When a small silicon bridge is heated electrically and a voltage applied across the device, a plasma is formed in a few microseconds which reaches temperatures greater than 2000 K, while metal wires can also be exploded into a plasma, as used in exploding bridgewire detonators, this require high voltage (800-2000V) and hundreds of amperes of current. The same plasma effect can be created with a silicon bridge at low voltage and 10-20 amperes of current pulse. Silicon is also an efficient conductor of heat, this effect can be used to design bridge with low thermal impedance, thus improving safety.

The present work develops a new means for igniting explosive materials. The volume of semiconductor bridge (SCB) is over 30 times smaller than a conventional hot wire. We present in this paper a description of SCB design and processing, physics of SCB operation, and test results for discharge experiment. We believe that the present program has a potential for development of a new igniter.

2 SCB Fabrication

Semiconductor bridge, SCB, is the small, rectangular, shaded area denoted in Figure 1; it is formed out of the heavily doped silicon area enclosed by the dashed lines in the Figure. The width of the bridge, w, is determined by the width of the narrow silicon region connecting the large silicon pads, and the length of the bridge, L, is defined by the spacing of the overlaid aluminum land. Typical bridge dimensions for a one-ohm device are 100-μm long, 300-μm wide and 5-μm thick on a square chip; the aluminum lands are approximately 1-μm thick. The lands provide a means for electrical connection to the bridge. Polysilicon-on-silicon (POLY) has been used for processing SCBs.

The cross section (A-A) of an poly SCB is graphically outlined in Figure 2. Although Figure 2 shows only one SCB being formed, an entire wafer or wafer section was processed at a time, producing hundreds of SCBs simultaneously. Initially, a dense silicon dioxide layer is deposited on the silicon wafer which provides electrical isolation from the wafer and an etchant barrier.

Next, a five micron undoped polysilicon layer in which the SCB will be fabricated is deposited on the silicon dioxide surface. Phosphorus is diffused into the polysilicon film from a phosphorus oxychloride spin-on dopant at 1100℃ for one hundred minutes. The resistivity obtained is approximately 8×10^{-4} ohm-cm implying a n-type dopant concentration of approximately 7×10^{19} P atoms/cm^3. An oxide layer is then grown on the surface to serve as a mask during the silicon etching. Photolithography techniques are utilized to generate a mesh structure in the form of an "H" in the doped polysilicon. The center leg of the "H" will be the SCB. The width of the center leg is the width of the SCB.

Next, aluminum ohmic contacts are fabricated on the two vertical legs of the "H" mesh structure. This is a normal IC metalization process in which the entire wafer is coated with one micron thick aluminum and photolithography is used to remove the metal in the appropriate locations. This mask to pattern the metal (Al) determines the length of the SCB. After this photolithography process, the structure is sintered for 30 minutes to obtain good ohmic contacts and to ensure good adhesion.

The finished wafer is diced and the chips are epoxied on a high strength ceramic header. Two one-mil gold wires are then welded from the kovar posts on the ceramic header to the aluminum lands on the SCB die.

3. SCB voltage characteristics

A. Experimental details

A DC square pulse with the rising time of 33 nano-second and the duration of 33 μsec is applied to the semiconductor bridge. The current of the DC pulse is controlled to be constant while generating and the voltage difference between aluminum lands was detected by the Tektronics-784A oscilloscope. The voltage difference was recorded in full time scale for 50 μsec from the beginning of the square pulse. All experiments have been done at room temperature and atmospheric pressure.

As shown in Table.1, different values of the current have been applied for various samples which have different resistance due to the difference either/both in the dimension of the bridge or/and in the resistivity. Considering the internal resistance, 1 Ω, of our discharge firing circuit we may estimate the applied maximum bias for the bridge as shown in table 1.

Table 1. Experimental conditions for different samples

Sample No.	dimension of the bridge(μm^3)	Resistance (Ω)†	Maximum bias (V)	Applied current(A)
1	100×100×2	2	20	10
2	100×200×2	1	15	15
3	100×300×5.3	1.8	27	15

† the resistance measured by the four point probe method

B. Result

Figure 3 shows the oscilloscope image of the voltage measurement for the sample #1 (produced by Quantic Co.). The horizontal direction is in time scale with the grid interval of 10 μsec and the vertical direction represents the voltage difference with the grid interval of 5V. Two distinct peaks are noticeable, the one at the beginning of the acquisition and the other in several micro seconds. Right after the second peak the constant voltage value is maintained until the end of the applied pulse. We call this interval of time the late time discharge (LTD) time and the meaning of LTD will be discussed below. The onset time of the LTD is about 4.5 μsec in this case. In Fig. 4 we have a similar voltage variation to that in Fig. 3 except that the second peak is not distinguishable. The onset time of the LTD is about 16 μsec. We present the data of voltage measurement for our test sample #3 in Fig. 5. The first peak is quite broad and the second one is missing. The onset time of the LTD is quite difficult to determine but it falls around 20 μsec.

C. Analysis

When a DC square pulse with the rising time of less than a few hundred nano second and the duration of more than several micro seconds is applied to the conventional SCB one can identify two distinct peaks of voltage as a function of time. It has been observed that the occurrence of the second peak and the LTD is influenced by the rising time. When the rising time of the pulse is longer than several micro second, no LTD has been observed(4). The second peak of voltage in time scale is relatively sharp but not always appear in the present cases *i.e.*, it is missing in the case of sample 2 and sample 3.

The full width at half maximum (FWHM) of the first peak varies from case to case. They are approximately 2 μsec, 3 μsec and 6 μsec for the sample 1, 2, and 3, respectively. The onset times of the LTD are 4.5 μsec, 16 μsec, and 20 μsec for the sample 1, 2 and 3. One may notice that there is some relation between the FWHM of the first peak and the onset time of the LTD, *i. e.*, the wider the FWHM, the later the onset of the LTD is.

We may separate the voltage (or power) versus time curve by four different stages in the time scale as,

-Stage 1: the voltage increases rapidly and reaches a maximum of the first peak,

-Stage 2: the voltage decreases abruptly but its time dependence is not steep as much as in stage 1, and reaches a plateau-like minimum,

-Stage 3: the voltage increases slowly in the beginning of the stage and it increases abruptly. The maximum of the second peak whose voltage value is not less than that of the first peak. The second peak is missing in the case of sample 2 and 3. The reason of the absence of the second peak will be discussed below.

-Stage 4: the voltage remains constant as the second peak is missing or decreases rather slowly and reaches quasi-constant value until the end of the applied pulse as the second peak appears.

By comparing the voltage vs. time data with the high speed flaming camera image (by Sandia Lab(4)) which enables one to see the magnified view of the bridge at every micro seconds, we may explain intuitively the voltage characteristics as followings:

In stage 1 the electrical resistance of the bridge increases according to the application of a DC square pulse and reaches a maximum which is supposed to be equal to the low-voltage resistance of the bridge. In the case of sample 1, we applied 10A DC square pulse and the low-voltage resistance of the bridge is 2 Ω then the maximum voltage should be equal to 20V. Actually the value of the first peak from the base line in Fig.3 is 20V. These are the cases for other samples. The steepness of the curve in stage 1 which is almost the same in all cases should be equal to that of the applied DC pulse, in other words, it is strongly related to the rising time (33 nano seconds in our case) of the applied square pulse. No apparent change of the state of the bridge has been recorded in the high speed flaming camera image until the end of the stage 1.

The voltage decreases according to the reduction of the dynamic impedance of the bridge in the stage 2. In the case of the sample 1 and 2 the dynamic impedance of the bridge is reduced to a third of its static maximum impedance. On the other hand it is reduced only less than a half in the case of the sample 3. The reduction of the dynamic impedance is the consequence of the electric discharge. This discharge process is similar to the avalanche breakdown in the case of the pn-junction or conventional solid-state plasma processing. In the high speed flaming camera image we could see that the bridge starts to melt from the edges (in the case of the Sandia report) and it develops into the middle of the bridge in this stage. The resistance of the bridge is reduced accordingly which is due to the fact that the resistivity of the liquid state of the semiconductor is an order of magnitude smaller(5) than that of the solid state. However, in the present experiments the voltage value at the end of the stage 2 is not 10 times smaller than the maximum voltage V_{max} at the end of the stage 1, but it is only about a half or a third of V_{max}. The reason of the elevated dynamic impedance at the end of the stage 2 may be due to the facts that the bridge partially remains as solid state, or some part of the bridge sublimates to the vapor state.

At the end of the breakdown some of the ions are vaporized upon further heating and liquid portion which enables the current to flow with relatively low impedance is diminished. When most of the bridge is vaporized the dynamic impedance increases suddenly at the end of stage 3, then the plasma discharge will occur as the applied square pulse meets the appropriate condition. According to the report(4) (Sandia Lab.) one of the required conditions for the LTD is the current for a given cross sectional area of the bridge. They drove the empirical relationship between the threshold current for the LTD and the SCB cross sectional area for several bridge geometries:

$$I_{th} = 0.017\ W \times t$$

where I_{th} is the threshold current, W, t are the width and the thickness of the bridge in the unit of micro meter, respectively. According to this relation the threshold current for our samples are 3.4A, 6.8A, and 27A for sample 1, 2 and 3. Hence the applied pulses for the sample 1 and 2 were sufficient for LTD while it was too low to obtain LTD in sample 3. In this context we can understand that the LTD in the case of sample 3 is not clearly defined.

In the final stage, the plasma discharge process happens and it lasts until the end of the pulse. It is believed that the heated plasma is produced during the LTD which is capable of thermally igniting granular explosives. The interpretation of the dynamic impedance of the heated plasma is little known up to date.

It has been suggested that the energy transfer mechanism exist which effectively couples the bridge to the adjacent explosive by the convection from vaporized bridge products permeating explosive. The current pulse vaporizes the bridge and heats the silicon plasma that forms. The hot silicon vapor permeates the powder pressed against the bridge and condenses on the explosive particles heating them to their ignition temperature. However, it is still unknown that clearly defined LTD is essential for the ignition of explosive.

According to our update experiments a small amount (a few mili gram) of explosive LS (lead styphnate) which was attached on the bridge with paste was fired successfully in the case of sample 3 with the 15A of the DC pulse. The voltage variation with time is similar to Fig. 5 in which the LTD was not clearly defined.

4. Applications

A. Actuator

It has been described by Sandia group(6) that a standard bridgewire actuator can be replaced by the same device retrofitted with an SCB. SCB assemblies provided significant saving in weight and volume both in terms of the explosive device itself and also because of the compact and low mass firing set.

B. Dual mix device

Two SCB devices developed (actuator/igniter and a detonator) are described by Tarbell and Sanchez(7). This single firing set is used for both the detonator and the actuator/igniter obviating the need for two separate firing systems. A dual mix device was developed to satisfy the requirement of a component that could act as an actuator (gas generator) as well as an igniter (plasma producer).

C. SCB Slapper

It has been considered the development of an SCB slapper detonator. This device is similar in design to other SCB devices but has a flyer material coated over the bridge region. When the SCB functions, the plasma discharge propels the flyer material into a secondary explosive such as HNS (hexa nitro stilbene) or PETN (penta erythrital tetra nitrate). The flyer impact on the secondary explosive causes a prompt shock initiation. An order of magnitude lower cost per unit and lower energy requirement for operation will be distinct advantages.

D. Detonators

Several insensitive explosives have been evaluated for possible detonator applications with SCB's. These materials all required a run-up to detonation from the impulse received from the SCB. The run-up may be considered as a deflagration-to-detonation transition process. It has been reported(6) that PETN detonator functioned in an appropriate conditions for SCB operation. In detonator applications a comparatively high voltage (an order of KV) is applied within very short time (about a micro second) in order to obtain an extremely quick response.

5. Comparison of SCB and hot-wire devices

Features peculiar to the SCB which distinguish it from hot wire or thin metal films or foils are summarized in table 2. As noted earlier the volume of an SCB is approximately thirty times smaller than that of a conventional bridgewire. This allows the firing set to rapidly heat the bridge to the plasma discharge. In order to take advantage of this property of SCB, we require that the input current pulse have a 100 ns or less rising time. At slow heating rates to currents less than 10 amperes the SCB will, in fact, function like a hot wire and conductively heat the powder to ignition even though the bridge did not form a plasma discharge. The unique signal input required for SCB to proper function is one of the distinguishing features of this device.

Table 2. A comparison of the physical properties of an SCB with a typical hot-wire material.

	Conventional Hot-Wire	SCB
material	Tophet C	heavily doped poly Si
resistivity (Ohm-cm)	1.1×10^{-4}	7.6×10^{-4}
bridge R(Ω)	1.0	1.0
melting point (℃)	1350	1410
bridge volume (m^3)	275×10^{-8}	7.6×10^{-8}
thermal conductivity (cal/cm s K)	0.2	0.17
specific heat (cal/g K)	0.11	0.20
temperature coef. of resistivity $\rho(T)$	positive	negative

Because an SCB has a negative temperature coefficient of resistivity, as it is heated its conductivity increases. In contrast, metals increase in resistance with temperature. This implies that a small diameter; metal bridge-wire may act like a fuse. Consequently, as the bridge-wire is heated, it can melt causing the bridge to open before the explosive component can ignite. In contrast, if a current pulse of sufficient magnitude and duration is applied to an SCB it will discharge and the device will function.

6. Summary

It has been demonstrated that one can generate a plasma discharge from SCB in order to ignite the explosive materials. Through the development of the SCB it was demonstrated that SCB will function as an initiator of the igniting system which works with low input energy and fast functioning time. Furthermore it is highly safe device and the replacement for variety of electro explosive device. In conclusion, we believe that SCB may have many other pyrotechnic applications.

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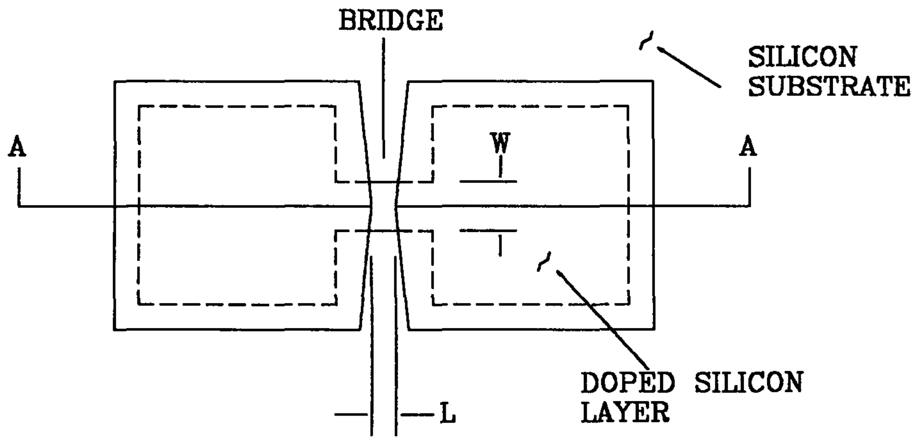

Figure 1. A sketch of a SCB. The bridge is the doped silicon area between the large aluminum lands. The large land/silicon overlap minimizes ohmic contact between the land and the silicon. The lands provide a means for electrical input to the bridge. Current flows from land to land through the bridge

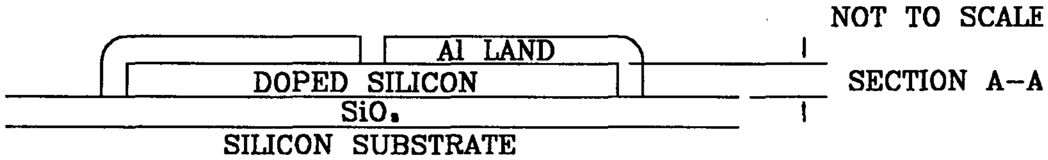

Figure 2. Cross section of a SCB.

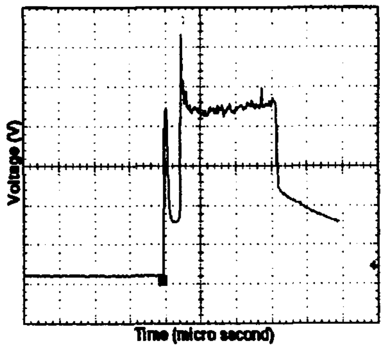

Figure 3. The voltage measured across the SCB device in the case of sample 1.

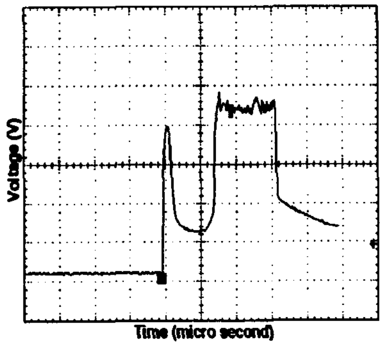

Figure 4. The voltage measured across the SCB device in the case of sample 2.

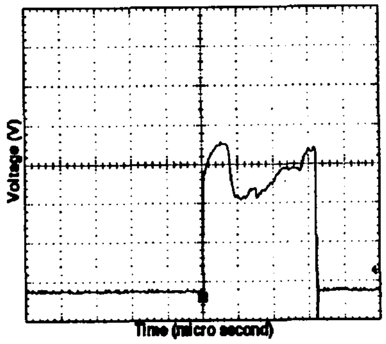

Figure 5. The voltage measured across the SCB device in the case of sample 3.