AN INTRODUCTION TO SEMICONDUCTOR INITIATION OF ELECTROEXPLOSIVE DEVICES

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ABSTRACT

Conventional electroexplosive devices (EED) commonly use a very small metal bridgewire to ignite explosive materials i.e. pyrotechnics, primary and secondary explosives. The use of semiconductor devices to replace "hot-wire" resistance heating elements in automotive safety systems pyrotechnic devices has been under development for several years. In a typical 1 amp/1 watt electroexplosive devices, ignition takes place a few milliseconds after a current pulse of at least 25 mJ is applied to the bridgewire. In contrast, as for a SCB devices, ignition takes place in a few tens of microseconds and only require approximately one-tenth the input energy of a conventional electroexplosive devices. Typically, when SCB device is driven by a short (20 μs), low energy pulse (less than 5 mJ), the SCB produces a hot plasma that ignites explosive materials. The advantages and disadvantages of this technology are strongly dependent upon the particular technology selected. To date, three distinct technologies have evolved, each of which utilizes a hot, silicon plasma as the pyrotechnic initiation element. These technologies are 1.) Heavily doped silicon as the resistive heating initiation mechanism, 2.) Tungsten enhanced silicon which utilizes a chemically vapor deposited layer of tungsten as the initiation element, and 3.) a junction diode, fabricated with standard CMOS processes, which creates the initial thermal environment by avalanche breakdown of the diode. This paper describes the three technologies, discusses the advantages and disadvantages of each as they apply to electroexplosive devices, and recommends a methodology for selection of the best device for a particular system environment. The important parameters in this analysis are: All-Fire energy, All-Fire voltage, response time, ease of integration with other semiconductor devices, cost (overall system cost), and reliability. The potential for significant cost savings by integrating several safety functions into the initiator makes this technology worthy of attention by the safety system designer.

INTRODUCTION

Most electroexplosive devices (EED) are initiated with a metallic bridgewire that is electrically heated as a firing current passes through the bridgewire . In a typical 1 amp/1 watt EEDs where typical firing current of 3 - 5 amperes are used, ignition takes place a few milliseconds after a current pulse of at least 25 mJ is applied to the bridgewire. The bridgewire material is selected from high melting temperature metal alloys that are corrosion resistant, tough enough to withstand loading pressures, and that can be welded or soldered to electrical connectors. An electrical current passes through the bridgewire, and generates heat energy in proportion to the square of the current multiplied by resistance. Since the bridgewire resistance increases as the wire gets hotter, the heating is a dynamic phenoma depending on variables that control the rate of heat conduction away from the wire and the rate of heat generation by the current flowing through the bridgewire. If the device is exposed to potentially hazardous electromagnetic radiation that could heat the bridgewire inadvertently, then the bridgewire's thermal and electrical impedance resistance can be lowered so more electrical current is required to initiate the explosive materials. Such bridgewire designs have evolved over many years, with a variety of configurations, materials and processes.

The use of silicon as a substitute for the metallic bridgewire presents several potential advantages and additional design challenges. Silicon is a crystalline semiconductor material that has properties much different from a typical metal. First intrinsic silicon has a relatively high resistivity; on the order of 100 ohm-cm or more; the pure it is, the higher the resistivity. Silicon is also brittle, it can not be drawn or bent like metal. For applications to electronic devices, the silicon is melted and grown as a single crystal. It is then sawed into wafers which are in turn processed by the application of various dopants and conducting layers. If impurities such as phosphorus atoms are implanted and diffused into the surface of a silicon wafer, the conductivity can be made many orders of magnitude higher; approaching the conductivity of a metal. Silicon is much different from metal bridgewires in that when heated electrically, it forms a high temperature plasma (ionized gas) which becomes very conductive and rapidly coverts 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 of 2100-2600°K. This is to be compared to the 900°K temperature of a typical hot bridgewire achieved in 1-2 milliseconds when electrically heated. While metal wires can also be exploded into a plasma, as used in exploding bridgewire detonators, this requires high voltage (500-2000V) and hundreds of amperes of current. The same plasma effect can be created with a silicon bridge at 10-20v and 10-20 amps of peak current.

Silicon is also an efficient conductor of heat, and this effect can be used to design bridges with very low thermal impedance. This improves safety.

- To take advantage of the desirable properties of silicon in electroexplosive device applications, it is necessary to create a structure which can:be electrically heated to a high enough temperature to start the plasma;
- provide an electrical connection to the device that can sustain current flow during the initial heating process and during plasma discharge;
- support the silicon in a manner sufficient to withstand the pressing of explosive powders and subsequent thermal cycling, shock and vibration environments.
- provide a method for heat sinking the bridge.

BACKGROUNDS

The semiconductor bridge was invented in 1968 by Hollander. The Hollander semiconductor bridge structure was much like a bridgewire device; cutting the silicon into a long, thin shape and soldering it to two posts on a conventional header. This device had all the characteristics described above, and Hollander described an array of dopant materials that could be used to achieve varying resistivities of the silicon for different electrical requirements. This invention went largely unnoticed until the Sandia National Laboratories began to explore the phenomena. In 1987, R.B. Bickes and several other scientist at Sandia developed a better method of attaching the semiconductor bridge to a header. They created large conducting pads on the silicon die which were, in turn, metallized for connection to a conducting wire or strip. These large pads provided a low resistance contact with the semiconductor bridge itself and expedited the handling and attachment of the bridge to a header. The semiconductor bridge itself was, however, identical to the Hollander design.

In 1990, D.A. Benson and others at Sandia invented a new and novel manner of achieving the initial heating of the silicon; Benson covered the silicon bridge with a thin layer of tungsten applied by chemical vapor deposition. Thus, instead of providing the heavy doping with impurities and the subsequent wafer processing required by the Hollander technique, the tungsten/silicon (WSi) bridge is constructed by a single masking and oxide etch with subsequent exposure to the tungsten containing chemicals which selectively deposits tungsten on the exposed silicon. After the bridge is created, the tungsten-silicon bridge can be processed and attached by the available techniques, just as the doped silicon bridge. The thin layer of tungsten can be controlled so as to adjust the initial resistance of the device. Once the silicon reaches the plasma state, due to electrical heating by the tungsten, it behaves like the plasma created by the heavily doped silicon.

One would expect this very high temperature, exploding ball of plasma to ignite explosive powders easily and reliably. If the powder is homogenous and of the proper particle size and is consolidated on the bridge properly, this is exactly what occurs. However, one other characteristic of the silicon plasma that needs to be discussed is its short time duration. Most of the electrical energy is converted to heat during a brief period, typically within 1-30 microseconds. Since the reaction is so fast, the device consumes less energy that a wire bridge which might require hundreds of microseconds to reach ignition temperatures. As a semiconductor bridge fires and creates a plasma, a dramatic lowering of the bridge resistance occurs, thereby increasing the flow of current in the plasma. For this reason, the firing circuit should be constant voltage, constant energy, or a capacitive discharge circuit which supports the plasma generation effect. Constant current sources do not provide the short duration, high currents needed to drive the plasma formation. The energy storage capacitor in these circuits can be quite small (10-40 microfarads).

SCB DESIGN AND FABRICATION

A semiconductor bridge, SCB, is formed out of the heavily doped silicon. The most important factors in designing the SCB is the selection of appropriate substrate to provide no fire safety and the careful selection of bridge dimension to satisfy desired bridge resistance and all fire characteristics which will results in optimum ignition.

Two (2) materials, silicon-on-sapphire (SOS) and polysilicon-on-silicon (POLY), have been used for processing SCBs. Typical SCB consist of three regions namely substrate. bridge, and lands. Bridge is formed from the heavily doped silicon layer. The bridge thickness is determined by the thickness of the silicon layer on the wafer (substrate); the width of the bridge is determined by the shape of the doped region. The lands provide a means for electrical connection to the bridge by connecting them to the device input leads via appropriate interconnection method.

The fabrication of SCB require simple CMOS process, and an entire wafer can be processed at a time, producing thousands of SCBs simultaneously. Brief description of procesing of SOS SCBs is presented here. The processing begins with doping the silicon through diffusion of phosphrous from a phosphorus oxychloride source. Next step defines the desired silicon pattern using a mask and photoresist, this silicon pattern determins tha bridge width. Then lands are defined using mask and photoresist. The wafer is then diced into the finished individual chips.

SCB FUNCTIONAL CHARACTERISTICS

Upon application of low voltages or firing energies, typically via capacitive discharge firing unit, SCB forms a hot plasma. Heat transfer mechanism from the plasma to the explosive powder pressed against the SCB is via microconvection. As the SCB produces plasma, the plasma permiates up into the pores in the powder, and condenses onto the explosive particles heating them to their ignition temperature.

The low energies for plasma formation and ignition of explosive powders observed are due to the fact that SCBs are so much smaller than conventional bridgewire. This very small geometry also permits the rapid injection of energy into the SCB and, in addition, appears to favor very efficient energy transfer into the explosive material. The result is that SCBs function a thousand times faster than bridgewire.

Despite the low energy required for ignition with SCBs, efficient heat transfer from the silicon film to the substrate also provide good no fire characteristics. No-fire sensitivity test results indicate that one (1) ohm SCB devices can greatly exceed the present 1 A/1 W criteria.

Through development program it was demonstrated that SCB devices are low energy, fast functioning, and safe devices for replacement for veriety of electro explosive device.

SCB APPLICATIONS

While there are both performance and cost advantages in using semiconductor bridges in electroexplosive devices, there are also disadvantages which must be addressed in any particular systems application. A major disadvantage is simply changing the initiator in a proven system; if requalification costs are involved they may be greater than the savings that accrue. In some applications of electroexplosive devices, performance is not an issue; the existing systems have been used for many years, they work fine the way they are, and there is no reason to change. Any change involves risk, and if there are no benefits, why take any risks?

On the other hand, the benefits that can accrue from modern semiconductor initiator technology are:

- Lower energy required (up to 90% less) for equivalent levels of HERO, ESD and no-fire current protection. The semiconductor bridges can be designed to function over a range of energies. Hence, to make the device "safer", more energy is required to reliably function the device. This tradeoff benefits the semiconductor bridge since the response curve is non-linear; hence no-fire and all-fire currents can be close together.

- Fast function time.

- High temperature plasma output (6000°K) allows ignition of less sensitive explosive materials.

- Passes 1 amp/1 watt/5 minutes no-fire.

- Additional functions can be integrated into the initiator, such as sensors, diagnostics, logic, BIT and firing circuits, this can save system costs in components and labor for installation.

- Better reliability through elimination of low strength bridgewire connections and use of a hot plasma to ignite the ordnance material.

- Lower cost, through the use of existing semiconductor assembly processes and readily available components from multiple sources. (This savings may require adaptation to new interface requirements).

The disadvantages of the semiconductor bridge technology are:

- Limited established, cost-effective sources are available for production.

- The firing circuit must be low impedance, that is, relatively low parasitic resistances in the circuit. (Note: The tungsten/silicon technology can tolerate higher impedances than the doped silicon.)

- Lack of experience and historical data to verify performance. (However, the Sandia National Laboratory has done extensive experimental and modeling work to verify the potential of high reliability. Quantic is currently sponsoring more work at Sandia to further develop the WSi bridge technology.)

- A major disadvantage of semiconductor bridge technology in the past has been that the bridge attachment has been unreliable due to the techniques used.

FABRICATION OF SCB EED

While the theoretical advantages of semiconductor bridge technology looks promising, this has to be translated into a producible, reliable and low cost initiator. The basic criteria for achieving this are:

- Devise an electrical connection process that is reliable (not disrupted during powder pressing, thermal cycling or vibration and shock), has low parasitic impedances, and can provide adequate current for the initial heating phase and the plasma generation phase.

- Provide good thermal connections between the die and the header assembly so that unintentional function from extraneous electrical energy sources is effectively prevented.

- Control contaminants which could jeopardize the shelf life of the device through corrosion or energetic material degradation.

- Provide a good hermetic seal for the device in order to assure long shelf life and long term reliability.

- Use highly automated assembly processes in order to minimize labor costs and assure effective statistical process control on assembly processes.

- Seal the backpressure created from the ordnance when functioned.

These design goals have been achieved by a new series of semiconductor electroexplosive devices designed and built by Quantic Industries, and described here. This product line is called the QWASI® (Quantic W and Si) Bridge initiators.

The heart of this design is new method for attaching the semiconductor bridge die to the header assembly (patent applied for). Previous methods have used thin wires or strips of a conductor bonded to the metalized pads on the semiconductor die. The problem with this and similar methods is that the explosive powder must be pressed onto these bonds at consolidation pressures of 10,000 p.s.i. and higher. This causes some of the bonds to break immediately; these failures can be detected by simple testing of the bridge continuity. The more troublesome failure occurs after the device has been thermally cycled, with the relative motion of the powder and the bridge causes stress on the bonds that cause subsequent breakage. Testing at Quantic has revealed that simply letting the loaded initiators, assembled using wire bond processes, set for a few months can result in significant failures after loading.

To overcome this problem, and to reduce production costs, Quantic invented a new method for attaching the die to the header and electrically connecting the bridge electrodes to the conducting pins in the header. This method also allows the addition of complex circuits to accommodate other components within the initiator. The semiconductor bridge, fabricated by either the Hollander (doped silicon) or Benson (tungsten overlay) or Baginski (junction diode) method can be used with this attachment process. These components can now be assembled using conventional automation equipment commonly used in the semiconductor industry. The final powder loading is accomplished by attaching a load sleeve to the header, loading and pressing the powder(s), and closing the assembly with a resistance welded can. Typical specifications for this header/closure assembly are:

Hermeticity	1 X 10^{-8} cc/sec @ 1 atm.pressure differential
Insulation Resistance	100 MΩ @ 100 VDC
Temperature Cycling	Method 1010, MIL-STD-883, Condition A to D
Thermal Shock	Method 1011, MIL-STD-883, Condition A to D
Lead fatigue	Four 90° bends with 1 lb. load
Gold Plating	MIL-G-45204C, Type I, II, III

APPLICATION OF SCB EED

In evaluating the wisdom of incorporating this new technology into a new design, or for retrofitting an existing design, several issues must be examined.

- The extent of the qualification program required to certify a new device.
- The number of units that will be consumes, their unit cost and a reasonable discount factor to be applied to future cost savings.
- The system benefits to be derived from fast function time, reduced energy requirements and integrated functions in the EED.
- The value of cost savings due to reduced procurements costs, reduced logistic support with longer life components and reduced component costs in the firing circuits.

Examples of applications for these new ignition devices include:

Attitude Control Motor Initiators
Parachute Release Systems
Air Bag Vehicle Safety Initiators
Rocket Motor Igniters
Flare and Chaff Dual Dispensers
Projectile Fuze Detonators

Before selecting a particular EED for a system application, the above trade-offs for old vs. new technologies need to be considered.

SUMMARY

It was demonstrated that SCBs can ignite explosivess with very low input energies to the bridge. Despite the low input energies for ignition, SCB explosive components are explosively safe passing both no-fire, ESD and EMI/RFI requirements. SCB chips can be economically processed that contain sophisticated circuit elements to provide additional safety and precise timing delays. Finally, SCB igniters can be mass produced using cost effective high throughput asssembly techniques.