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Light-Activated Solid-State Opening Switch

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PREFACE

This report documents research conducted on solid-state opening/closing switches for inductive energy store. This technical report was presented at the 6th Electromagnetic Launcher Conference in Austin TX on 28 Apr to 1 May 92.

This work was funded by the Electromagnetic Launcher Technology Branch (WL/MNSH) of the Analysis & Strategic Defense Division of the Air Force Wright Laboratory at Eglin AFB FL under the Kinetic Energy Weapons Program of the Strategic Defense Initiative. Mr. Mark W. Heyse from WL/MNSH and personnel from W.J. Schafer Associates (WJSA) in Chelmsford MA performed the work during the period of Apr 90 to Mar 92 at WJSA in Chelmsford MA.

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Light Activated Solid-State Opening Switches

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Abstract — Light-activated solid-state opening switches are shown to be a viable approach for switching inductive circuits. Measured photoswitch performance indicates that light-activated opening switches have the power density ratings needed to develop compact inductive power systems.

I. Introduction

Inductive energy storage is an attractive approach for compact power systems, but has been hindered by the lack of fast and reliable opening switches that can handle high commutation voltage and current. Early efforts at developing opening switches (i.e. mechanical, explosive, and plasma opening switches) have shown the need for solid-state devices to achieve fast switching characteristics with long lifetime and high reliability. Conventional solid-state opening switches like GTOs, mosfets, and IGBTs have proven too bulky and costly for compact systems, so that alternate solid-state opening switch approaches are needed in order to make inductive power systems practical.

This paper describes the development of light-activated silicon opening switches for high power inductive storage circuits. Light-activated switches employ optical trigger power to inject photocarriers in the switch in a controlled manner (both spatially and temporally). This is a key advantage because carrier injection determines both voltage and current distribution in the device, so optical trigger control can be used to avoid avalanche breakdown and current constriction during commutation. As discussed below, high average power operation has also been demonstrated. Thus light-activated switches have the power density rating and commutation control needed for compact inductive opening switch applications.

II. Light-Activated Opening Switch Approach

A light-activated opening switch is a bulk semiconductor material with heavily-doped contact electrodes, as illustrated in Figure 1. Illuminating the bulk region generates photocarriers that carry external circuit current. The device is turned off (or opened) by removing the optical trigger source, which allows the carriers to either recombine in the bulk, or to be swept out to the contact regions where they recombine. For a uniform carrier distribution in the substrate, and a bulk carrier lifetime τ , less than a carrier transit time, the on-state resistance of the photoswitch is:

$$R_s = \frac{x^2 E_{ph}}{\eta P_o \tau \mu} \quad (1)$$

where x is contact separation, E_{ph} is bandgap separation, η is photon/carrier conversion efficiency, P_o is optical power, and μ is carrier mobility. Equation 1 assumes that switch thickness is approximately one optical absorption depth ($1/\alpha$) of the light trigger pulse and the optical window has an anti-reflection coating.

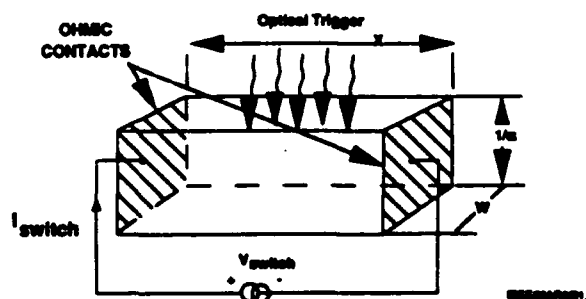


Fig. 1. Light-activated opening switch geometry.

WJSA has been actively involved with Eglin AFB in developing light-activated silicon opening switches. The goals of the opening switch program, along with demonstrated switch performance to date, are listed in Table 1. Commutation power density goals are approximately 3-5 times higher than conventional GTO specifications^[1], so that a major technology thrust was to develop highly compact photoswitch structures. A significant number of switch goals were accomplished, and technology paths have been identified for achieving performance improvements that can meet or exceed all switch requirements. For example, optical trigger characteristics, as well as substrate carrier lifetime and contact doping profiles, are key design parameters for optimizing opening switch performance^[2]. Space-charge formation at the contract/semiconductor interface was the primary factor that limited device performance below program goals. Photoswitch database and computer models indicate that Table 1 opening switch goals can be accomplished through careful design of the optical trigger and window system, as well as the silicon switch contact structure.

Table 1. Eglin Solid-State Opening Switch Program.

Program Goals: Develop a 250kA, 5kV solid-state opening switch package using parallel switch devices.		
	Device Goals	Demonstrated at Device Level
Peak Current Density	150A/cm ²	75A/cm ²
Off-state Blocking Voltage	5kV	5kV
Turn-off Commutation Voltage	5kV	500V
Forward Voltage Drop	2V	<1.5V
Rep-Rate	10Hz	>10Hz
Turn-on Time	20μs	20μs
Turn-off Time	75μs	20μs
Timing Jitter	<1μs	<50ns
Life	10 ³ shots	10 ³ shots
Switch Conduction Time	variable up to 5 sec	5 sec

Figure 2 shows a schematic cross-section of a photoswitch module that was tested during the opening switch program. The module contained 3 parallel switches that were flashlamp triggered, which was operated at liquid nitrogen temperature for enhanced steady-state switch thermal properties at long on-times (5 sec). Cryogenic temperature operation also minimized bulk silicon thermal runaway issues for Eglin switching requirements. The switches were able to support greater than 200V dc for more than 5 sec, and calculations show they can support 5kV for 10ms off-state times. Anti-reflection coatings on the photoswitch windows were not utilized due to the broad-band optical spectrum of the flashlamp trigger source.

The switches were thin silicon substrates mounted in a low inductance electrode configuration, and the total switch inductance for a 250kA system was less than 20nH. Figure 3 shows the laboratory hardware for the 250kA switch system. The 250kA switch assembly housed 12 parallel opening switch modules, and measured 9ft by 3ft by 4ft. The switch assembly was designed purely for laboratory use, and can be made significantly smaller for fieldable systems. The photoswitch modules contained 3-parallel opening switch substrates, and measured 12in long by 5in wide by 7in deep (including flashlamp and reflector housing).

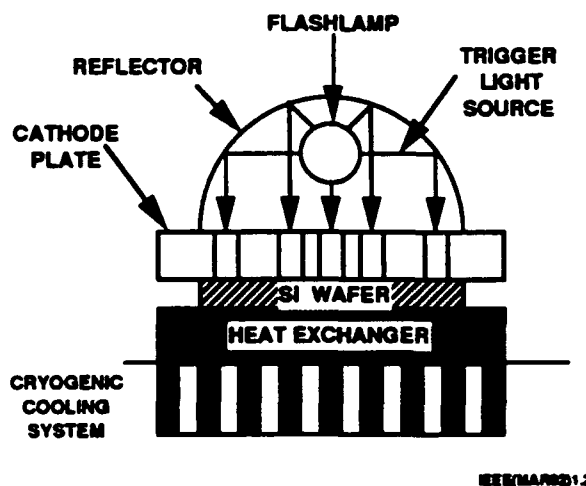
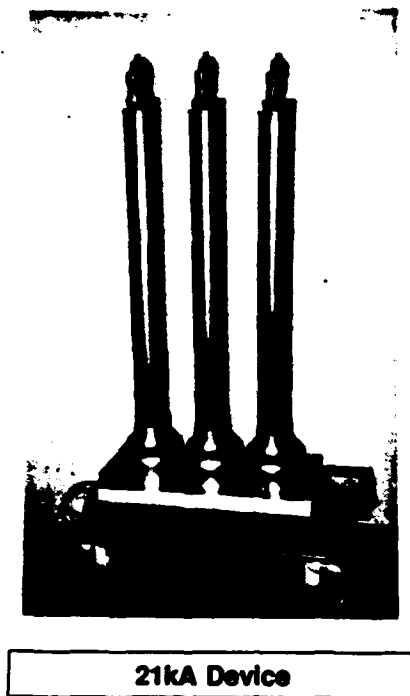
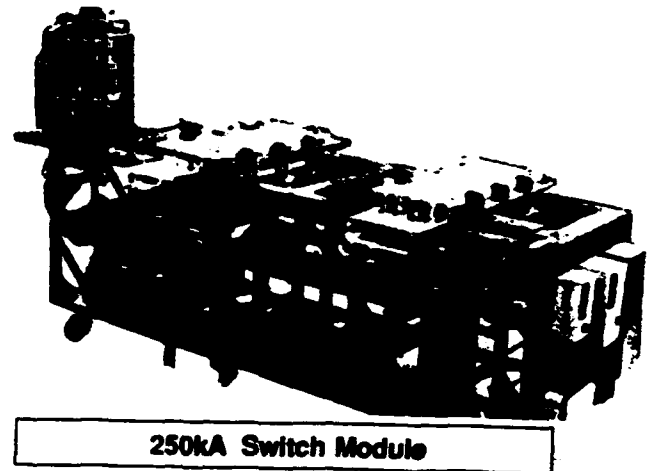


Fig. 2. Schematic of cryogenic opening switch module.



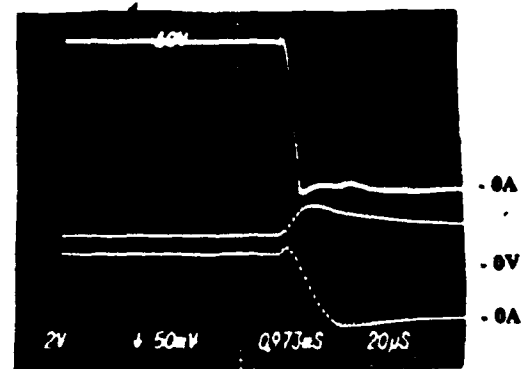
(a)



(b)

Fig. 3. (a) Opening switch module containing 3 parallel photoswitch substrates.
(b) 250kA switch assembly designed to house 12 opening switch modules.

Photoswitch commutation waveforms operating at 77°K are presented in Figure 4, and show current interruption times of approximately 20μs for flashlamp-triggered devices. The demonstrated 75A/cm² device current at less than 1.5V on-state voltage indicates that light-activated opening switches can be designed to meet compact high power inductive pulser applications. Technology development paths for achieving room-temperature switch operation with further volume reduction have been identified. For example, μ-channel cooling techniques combined with 1μm laser diode trigger sources, and graded pn junction structures will provide a high power density switch package^[4]. Thus light-activated opening switches have the power density ratings to be a viable solid-state opening switch technology for compact inductive power systems.



Top: I_{Lamp} : 50 A/8
Middle: V_{switch} : 10 V/8
Bottom: I_{switch} : 65 A/8
Horizontal: 20 μs/8

Fig. 4. Light-activated opening switch turn-off characteristics.

III. Summary

Light-activated cryogenic silicon opening switches were designed and tested in an inductive power circuit. Current interruption times of 20 μ s at current densities of 75A/cm² were demonstrated with flashlamp optical sources at 77°K. Photoswitch measurements and modeling show that electrical contacts, optical trigger, and window design are critical parameters in optimizing opening switch on-state current and voltage commutation. Technology paths have been identified for increasing photoswitch power ratings, and include room-temperature operation using laser diode arrays. The demonstrated high average power operation and power density capability of light-activated opening switches make them a viable switch technology for developing compact inductive power systems.

IV. Acknowledgements

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