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A High-powered Optoelectronic Switch with Picosecond Risetime

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Synopsis

A switch element has been developed so that a kilovolt step voltage should be supplied to a 50Ω transmission line with a subnanosecond rise time. The element is of silicon substrate with high purity and a pair of electrodes is attached by the evaporation process. The switch action is performed by the photoconductivity produced by the laser light pulse.

This paper deals with a preliminary analysis, manufacturing processes and experimental results of the optoelectronic switch. A performance of 320V output with less than 4 ns risetime was obtained with sufficient persistence for more than 2×10^5 pulse shots. This switch was successfully applied to an optical waveform monitor for laser light pulses giving a resolution less than 2 ns.

1. Introduction

A step electric signal with picosecond rise-time and a kilovoltage on a 50Ω line is often required for many applications in high-speed technologies such as Pockels-cell-drive or a streak-camera-trigger. Auston *et al.* proposed a silicon optoelectronic switch and demonstrated its subnanosecond response and 1.5 kV capabilities [1].

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Successive efforts have been done for higher voltage up to 10 kV by Mourou *et al.* [2], and for better versatilities with alternate gallium arsenide for Pockels-cell drive by Lee [3]. Mourou and Knox [4] emphasized a picosecond precision for in-line mounted gallium arsenide switch for a Pockels-cell drive.

The authors are developing a picosecond optical pulse waveform monitor using optical-fiber delaylines incorporated with a in-line Pockels cell for which a clearly step-shaped and high-voltage electric signal is necessitated. The optolelctronic switch is the indispensable element to this purpose.

This paper reports detailed fabrication processes of optoelectronin switches made of silicon and describes experimental results.

2. Requirements on the switch element

The performance characteristics required for the switch element are specified by the optical gate for a pulsed light signal with picoseconds duration, whose schematic diagram of the combined electro-optical gate is shown in Fig.1. The lithium tantalate ($LiTaO_3$) crystal steers the polarization direction of the transmitted light. This phenomenon is governed by the electric field intensity applied in the crystal. The conductors form a 50Ω transmission line since one picosecond corresponds to about a propagation length of 0.2 mm and a fully microstrip transmission line configuration is required for such high-speed operation. The values prepared for the silicon switch and the requirements from the optical gate are listed in Table 1. The source power is applied in a pulsed waveform for the

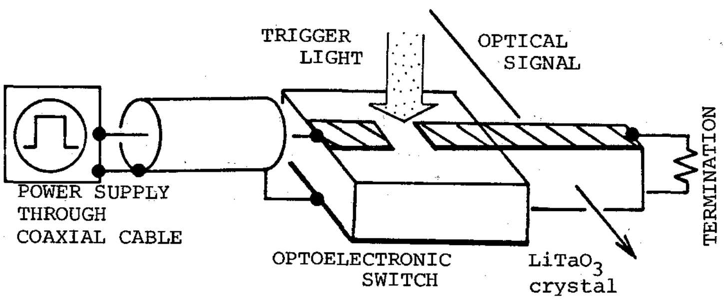


Fig.1 A configuration of an optical gate for a subnanosecond optical pulse utilizing the optoelectronic switch.

sake of the protection against a thermal breakdown. Provided that the rise time is enough short compared to a propagation time in the feeder line, the surge effect offers an advantage that a half supply voltage is enough for the same output voltage compared to a dc power supply. The $LiTaO_3$ crystal requires 2 kV to attain 90° swing in polarization direction along the 1 mm optical pathlength with 1 mm distance between electrodes. The high voltage and the rather low 50Ω characteristic impedance result in 20A peak current in the line conductors, which require good electrical contacts between different elements. The configuration of the switch is drawn in Fig.2.

Table 1 Requirements of an optical gate.

Source voltage	2 kV
Line characteristic impedance	50 Ω
Peak current	20 A
Applied source pulse duration	1 μs
Exciting optical pulse	
Wavelength	460 nm
duration	4 ns FWHM
Output pulse risetime	<< 4 ns

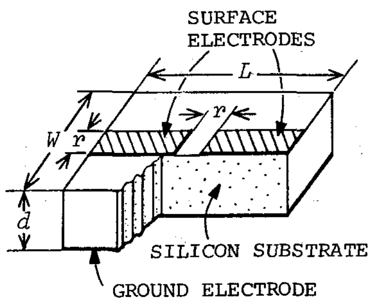


Fig.2 The configuration of the opto-electronic switch. Aluminium electrodes form a 50Ω microstrip line. Dimensions are d=1mm, W=L=10 mm, r=0.6~1.0mm.

3. Principles and analysis

The optoelectronic silicon switch utilizes the photoconductivity between two electrodes opposing on one surface excited by incident laser light pulse. Since the excitement take place very quickly after the injection of the laser light pulse, this switch action can operate very fast so far as the light pulse has enough short duration.

A time dependent transfer characteristics of this switch is analyzed as follows. For the sake of simplicity within an effective accuracy, the population of the electron-hole pairs are dependent on the x axis vertical to the surface of the silicon substrate into it. Let one absorbed photon generate a pair, then its density n at a depth x is expressed as

$$n(x) = n_s \exp(-\alpha x), \tag{1}$$

where n_s and α are density at the surface and a constant, respectively. Denoting the mobilities of electrons and holes as μ_n and μ_p, respectively, an equivalent conductance G between two electrodes as defined by Fig.3 becomes

$$G(t) = T_s \frac{e}{\hbar\omega} (\mu_n+\mu_p)\frac{1}{r^2} \int_0^t p(\tau)\exp(-\frac{t-\tau}{\tau_0})d\tau \tag{2}$$

where r stands for both width and distance of the electrodes, $p(\tau)$ is a temporal laser power, τ_0 the relaxation time of the pairs, and T_s, the light transmittance across the silicon surface, being given by

$$T_s = \frac{4n_r}{(n_r+1)^2} \tag{3}$$

with n_r a reflectance of silicon. Substancial values of silicon are listed in Table 2.

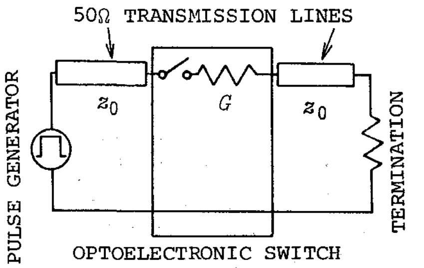


Fig.3 An equivalent circuit of the switch element connected to z_0=50Ω transmission lines on both sides.

Table 2 Parameters of silicon.

n_r	3.6	
$\mu_n+\mu_p$	2000	$cm^2/V\cdot s$
$\hbar\omega/e$	2.7	V
τ_0	100	ns

Resulting transmittance T, the temporal ratio of the output voltage to the input, is given by

$$T(t) = \frac{2z_0}{G^{-1}+2z_0}, \tag{4}$$

where z_0 stands for the characteristic impedance of the transmission lines. Though G is linear to the incident laser light energy as seen in Eq.(2), the transmittance shows saturation for $G^{-1}<<z_0$ correspond-

ing to a large exciting laser power. This results in a shorter rise-time in the output voltage than that of the incident light pulse power which is a replica of an object light pulse.

In Fig.4, the peak transmittance is shown for varying effective energy ηE of exciting light pulse. It is found that an easily available 2 μJ gives rise to a practical 90% transmittance.

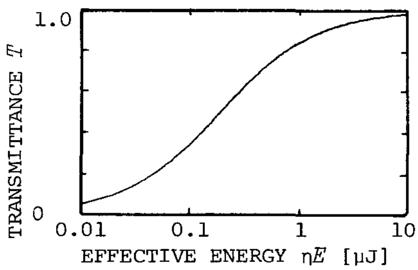


Fig.4 A calculated transmittance T for effective energy ηE of exciting laser pulse, where η is the quantum efficiency.

4. Test apparatus

Performances of the experimentally fabricated optoelectronic switch elements were tested with the system shown in Fig.5. In order to avoid reflectances which disturb the input and output waveforms, lengths of the coaxial lines are taken enough long, ten meters. The pulse generator is constructed of a L-C simulated transmission line and a miniature cold-cathode thyratron, KRYTRON (EG&G). The available repetition rate is one pulse per second because of the small capacity of a power supply and a thermal dissipation limit of the KRYTRON. A TEKTRONICS 7623A syncroscope with 4 ns risetime is used to monitor the output waveforms.

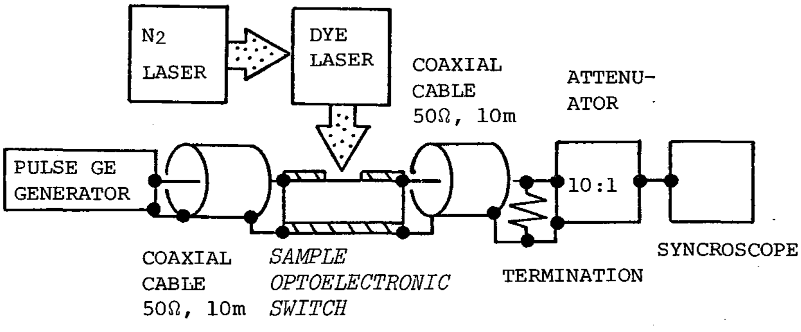


Fig.5 A test system for the fabricated silicon switch elements.

5. Experiments

Three different fabrication processes were tried and performances of the switch elements were tested. Fundamental process is common, that is, the electrodes are formed by evaporation with a metal mask shown by Fig.6 on a silicon substrate polished to a mirror surface.

Two silicon substrates of different purities, aluminium and gold for evaporated electrodes and diferent heat treatments were combined.

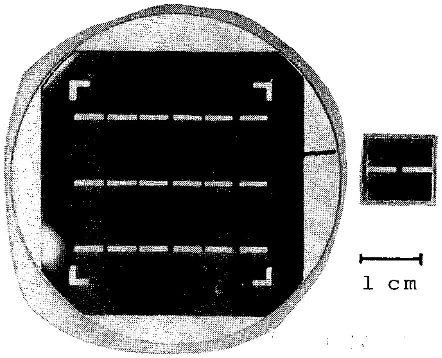


Fig.6 A silicon wafer with evaporated electrodes(left), which is scribed and split into a switch element after heat treatment(right).

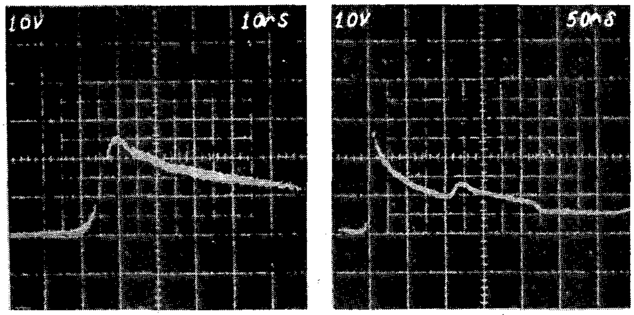
First sample was made of not so much pure, 10 Ω·cm, silicon substrates. This was for an establishments of processing only and the result for the switching performance was quite insufficient mainly due to the low specific resistance of the silicon wafer.

Table 3 Fabrication processes of the optoelectronic switches.

Sample	II	III
Material	Silicon single crystal, (111) surface 10^4 Ω·cm, p-type, 1 mm thick	
Surface treatment before the evaporation	Carborundum #1500	Alumina 0.5μ to a mirror surface
	Chemical etching HNO_3:HF ≒ 5:1, 20°C, 10 min.	
Electrode		
Material	gold	aluminium
Thickness	<1 μm	∿ 2 μm
Evaporation		
Pressure	10^{-5} Torr	< 10^{-6} Torr
Substrate temperature	200 °C	250 °C
Heat treatment after the evaporation	no	550 °C, 10 min. in flowing N_2 gas.

Second and third versions were fabricated with very pure silicon wafer with the specific resistance of more than 10^4 Ω·cm. Processing conditions are listed in Table 3.

Results of the test done with the system in Fig.4 for a sample prepared by the process II are shown by Fig.7. In Fig.7(a), the rise-time of the output is found as 6 ns. In Fig.7(b), an exponential decay due to the extinction of electron-hole pairs with time constant of 100 ns, and reflectance from the 10m coaxial line ends are observed. The peak transmittance T is 0.5. This sample was, however, broken down after some tens shots under 800V supply voltage, the gold electrodes being blown off. This was attributed to that the contact between the electrode and the silicon substrate was not enough tight and the gold electrodes were too thin.



(a) (b)

Fig.7 Experimental responses of a silicon optoelectronic switch II. Waveforms of output voltages are shown with different time scales. Supplied power is 100V dc and 25 V output is obtained with 6 ns rise-time.

The third version was designed for better persistence. Electrode material was changed from gold to aluminium which allows more thickness in evaporation with a lower ohmic power dissipation and prevent a formation of junctions at the metal and silicon boundary. More careful polishing was made for the surface for reducing a trap density ,and an accurate heat-treatment process was added to form a good ohmic contacts. A result is given in Fig.8 which shows a 4 ns risetime, close to the lowest limit of the syncroscope resolution, 3.5 ns, and 320 volts output. A more voltage is expected but was not tried because of a fear of electric discharge along the silicon surface. The persistence was remarkably improved and the element by this process is still alive after $2{\times}10^5$ shots with 300 volts output.

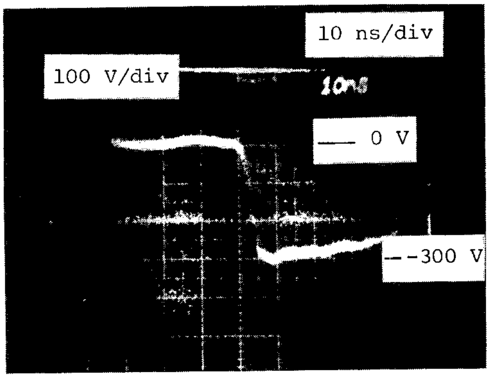


Fig.8 Response of the switch element III. A negative 800V step voltage is supplied through the coaxial cable. Output pulse hight is 320V and the rise time 4 ns,which is limited by the bandwidth of the syncroscope.

6. Application for an optical gate

The last version of the switch element was applied to an optical gate having been stated in section 2. The assembled optical gate of the $LiTaO_3$ Pockels cell combined with the silicon optoelectronic switch element is shown in Fig.9. A light pulse from a dye laser with wavelength of 460 nm was monitored by this gate for its shape. The result is shown in Fig.10. Principle of this method is to take a convolution of a light pulse as a signal and the step waveform generated by the optoelectronic switch with varying delay time. The original waveform is reproduced by calculation. Obtained waveform gives a 2 ns pulse width (full width at half maximum) which is consistent with a value expected from the dye laser and the N_2 laser design.

7. Concluding remarks

The fabrication process for a silicon optoelectronic switch was established. A combination of aluminium electrodes and a silicon substrate with high-purity of 10^4 Ω·cm specific resistance resulted in the best performance. Careful polishing before the evaporation of electrodes and precise heat treatment were necessary for satisfactory persistence.

Output voltage of 320V was obtained and the risetime is conjectured to be less than 2 ns from an experiment of optical gating.

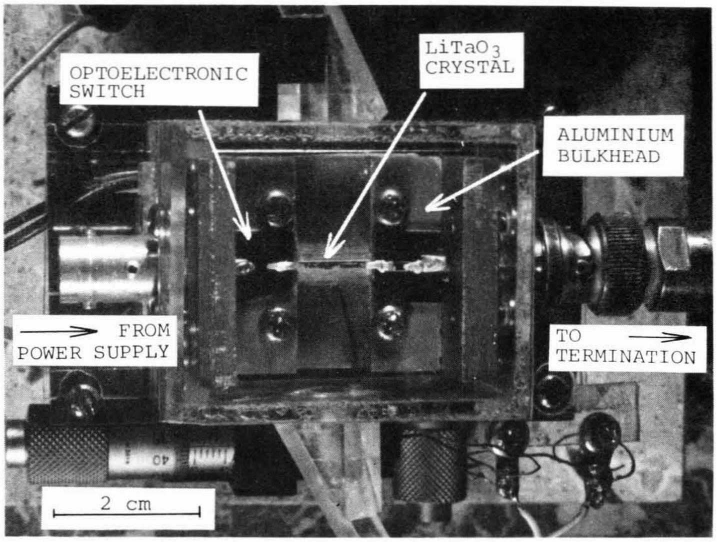


Fig.9 An optical gate consisting of the switch element and a $LiTaO_3$ crystal assembled on an aluminium bulk head which is temperature controlled within 0.1 °C accuracy. The assembly is accomodated in an casing of acryl resin for thermal insulation.

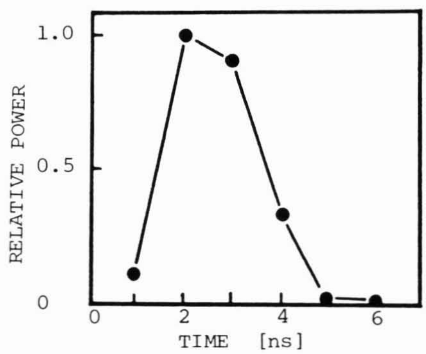


Fig.10 A result of optical-pulse monitoring for its waveform by the system utilizing the optical gate shown in Fig.9. A two nanosecond full width at half maximum is resolved.

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