

# Optimising the Performance of an Optically Controlled Microwave Switch

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**Abstract**—Optical control of microwave switches is an appealing concept for use in reconfigurable antennas as it eliminates the need for metallic biasing lines which may affect the performance of the wireless system. The ultimate goal of this study is to minimise insertion loss of a photoconductive microwave switch in the ON state whilst maintaining high isolation in the OFF state. Firstly, a parameter simulation study using different substrate materials, thicknesses and gap widths is presented to obtain optimised S21 results. The best performance is from a 1.2mm line using a 0.3mm gap. Secondly, the effect of passivation and texturisation on the photoconductivity and microwave performance of the silicon die is investigated. Passivation of the sample decreases insertion loss, however texturing the surface increases loss.

**Keywords**—Photoconductive switch; optical control; reconfigurable antenna; passivation; silicon; surface texturing.

## I. INTRODUCTION

Recently, a number of reconfigurable antennas have been demonstrated using optically controlled methods with a view to avoiding the inclusion of metallic biasing lines. Panagamuwa *et al.* presented a dipole antenna [1], where frequency and beam pattern can be reconfigured. Tawk *et al.* reported on a reconfigurable circular patch antenna for use in cognitive radio applications [2]. A steerable antenna array incorporating optically controlled EBG phase shifters is presented by Chauraya *et al.*, where a wide beam scan was achieved when operated by low power LEDs [3]. Optical control of microwave switches has been chosen over existing switching components such as PIN diodes as the associated circuitry needed to control these switches affects antenna performance in an adverse way.

As research continues into reconfigurable antennas and methods of switching, the potential of high linearity [4] and fast switching [5] make the photoconductive switch a good candidate to be used in wireless communication systems. Optimising the switch for high performance is key to increasing the number of reconfigurable antenna designers choosing to use photoconductive switches. Important figures of merit for microwave switches are low insertion loss and high isolation – the goal of this research is to identify potential methods that will improve switch performance in terms of these criteria.

Alex seems to have thoroughly enjoyed his placement year at Microsoft. He is keen to go back for a summer placement and hopes he can get a job in the research arm. He is settling in ok. Has perhaps forgotten some of his maths.

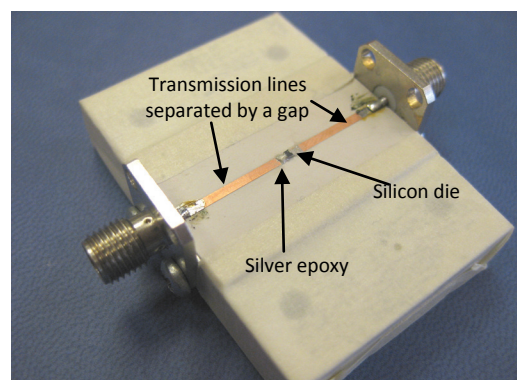


Fig. 1 Optically reconfigurable microstrip with a silicon switch

The photoconductive switches consist of a die of boron doped silicon, resistivity  $>10000\Omega$ , attached between two lengths of copper microstrip line, figure 1. When illuminated by light of a wavelength of 980nm, electrons in the silicon become promoted from the valence band to the conduction band and electron-hole pairs are created hence making the silicon conductive. The switch is in its ON state when illuminated which allows the RF signal to propagate through the silicon die.

Switch insertion loss is dependent on two main factors; switch topology and the number of free electron hole pairs, referred to as carriers, generated by illumination of the silicon. The light intensity focused on the silicon die can be easily varied during switch operation. The intensity of illumination required is dependent on what level of loss is acceptable in the application the switch is employed in. On the other hand, the switch topology cannot be modified during operation and so has to be optimised before fabrication.

The track width and gap width influence both insertion loss in the ON state and isolation of the switch in the OFF state. In this study, optimisation of the topology has been based around

a 1mm die of silicon, as the optical fibre delivering illumination has a 1mm diameter. For this particular size of silicon it is expected that there will be an optimum combination of substrate thickness, permittivity and gap width dimension between transmission lines that cause the best impedance match.

This paper aims to optimise switch topology by considering the use of different substrate materials. A 50Ω transmission line with a gap was designed using commercially available substrate materials of different permittivity and thicknesses. The substrate thickness and permittivity naturally determines the line width of a 50Ω transmission line.

A parameter study was then conducted varying the gap width to optimise both insertion loss and isolation. Flemish *et al.* were able to improve the performance of their optically controlled attenuator by optimising the dimensions of their component's layout [6]. Gevorgian links optical losses for an optically excited semiconductor to the width of the gap in the transmission line topology [7].

To consider the second aspect of maximising the number of electron hole pairs generated, conductivity of the silicon is dependent on these main factors:

- Silicon treatment – to improve light coupling into the die, to reduce defects in the silicon and doping to control OFF state conductivity
- Mechanical alignment and positioning of the light source
- Silicon thickness and wavelength of illumination to control distribution of conductivity in the die
- Light intensity of illumination source

Young *et al.* discussed growing silicon oxide on a silicon microwave switch to act as a passivation layer, thereby improving performance [8]. The use of surface texturing has been researched by the solar cell industry and has been successfully used to increase the light entering into solar cells. In the second section of this paper silicon which has been treated with these techniques is mounted onto the optimised switch topology. The effect of these techniques is quantified in terms of improvement of RF performance for a silicon microwave switch.

The benefits of this work include lowering insertion loss which from an application point of view will lead to an improved antenna performance. Since signal is subject to less loss this also allows increased power handling. Reduced insertion loss may also increase switch lifetime. The other benefit is the possibility of using a lower light intensity to control the switch due to the increased efficiency of the switch.

## II. SWITCH PARAMETER OPTIMISATION

The switch is simulated in IMST EMPIRE XCcel version 5.51 [8] as a 1mm × 1mm × 0.53mm die of silicon with a conductivity of 45S/m,  $\epsilon_r = 11.1$  and  $\tan\delta = 9.2$  in the ON state. In the OFF state the die has a conductivity of 0.035S/m,  $\epsilon_r=11.8$  and  $\tan\delta = 0.02$ . The die is attached with silver epoxy between two lengths of transmission line. It is assumed that the silicon has one bulk conductivity; this is a valid assumption

to make during this investigation as silicon performance is not being optimised in this part of the study and the same model for silicon is used in each switch topology.

Three substrates were investigated in this research, Rogers 3003 (R3003),  $\epsilon_r = 3 \tan\delta = 0.0031$ , Rogers RT Duroid 6006 (R6006),  $\epsilon_r = 6.12 \tan\delta = 0.0027$  and Taconic TLY-5 (TLY5),  $\epsilon_r = 2.2 \tan\delta = 0.0009$ . The effect that varying line width has on switch performance was considered by simulating different commercially available substrate thicknesses, 0.25-1.52mm. Line width is dictated by a 50Ω impedance match, varying between 0.74 - 3.8mm.

The effect that gap width between the two transmission lines has on insertion loss and isolation was also considered.

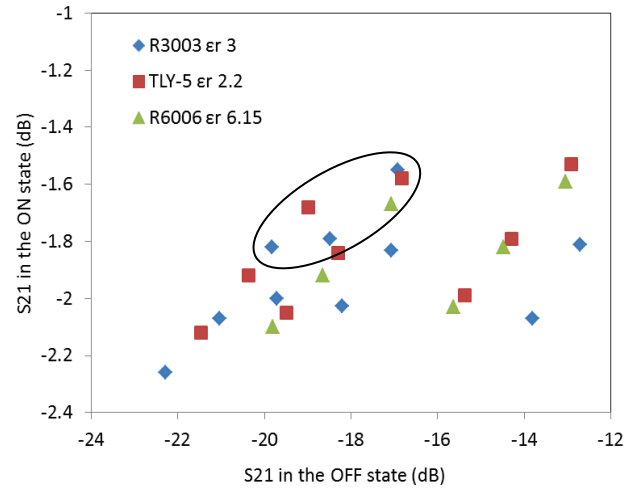


Fig. 2 Switch variations and their respective insertion loss and isolation values, markers represent different line and gap widths.

For this parameter in particular there will always be a trade-off between insertion loss and isolation – gap widths between 0.2-0.4mm were investigated.

Simulation results for 27 different switch dimensions were collected, and S21 results in both the ON and OFF states are presented in figure 2. The circle highlights data points with low insertion loss and high isolation – these cases have been investigated in more detail, Table I. Thinner substrates with a corresponding thinner line width produce superior results as unwanted capacitive coupling across the gap in the OFF state is reduced.

TABLE I  
OPTIMISATION PARAMETERS FOR THE TOP 6 SWITCH CONTENDERS AT 2GHZ

Substrate type	Substrate height (mm)	Track width (mm)	Gap width (mm)	S21 OFF (dB)	S11 ON (dB)	S21 ON (dB)	Impedance (Ω)
R3003	0.25	0.6	0.2	-19.8	-14.0	-1.8	36
TLY-5	0.25	0.74	0.2	-19.0	-14.9	-1.7	42
R3003	0.5	1.22	0.3	-18.5	-14.7	-1.8	44
R6006	0.64	0.9	0.2	-17.1	-15.1	-1.7	37
R3003	0.5	1.22	0.2	-16.9	-15.9	-1.6	45
TLY-5	0.5	1.53	0.2	-16.8	-14.4	-1.6	48

Line widths that closely match the dimensions of the silicon appear to produce better results. The currents on the transmission line are mainly on the outer edges and hence maintaining line width seems to improve results. The impedance of these transmission lines are more closely matched to 50Ω. Coupling across the gap is facilitated by the presence of conductive silicon. Hence it appears that silicon which is the same width or slightly larger than the line width encompasses the fringing electric field at the gap discontinuity.

The design incorporating Rogers 3003 substrate, height 0.5mm, gap width 0.3mm was used to continue the silicon optimisation process. This design presents an insertion loss of 1.8dB and an OFF state isolation of 18.5dB with an impedance of 44Ω. The substrate thickness is also double that of some alternate switch designs, leaving more scope for achieving these results during fabrication accounting for manufacturing tolerances.

### III. SILICON TREATMENT OPTIMISATION

Using the optimised switch topology discussed in section 2, silicon dice treated in different ways were mounted over the gap between transmission lines. The effect of passivation and surface texturing are considered. Table II summarises the silicon samples investigated.

TABLE II

SWITCH SAMPLES INCORPORATING DIFFERENT TREATMENT TO THE SILICON DICE

	Treatment	Depth of oxide (nm)	Carrier lifetime before dicing (μs)	Reflectance at λ=980nm (%)
A	Polished (untreated)	2 (native)	13.4	34.0
B	Polished (Passivated SiO <sub>2</sub> )	57	36.6	28.8
C	Textured 4μm pyramid base (Passivated SiO <sub>2</sub> )	57	29.5	8.4

#### A. Fabrication

1) *Silicon choice*: The higher grade float-zone (FZ) wafer was chosen over the typical Czochralski (CZ) type wafer used to manufacture solar cells. The wafer is lightly boron doped, with a resistivity of 10kΩ. One side only is polished. All these factors have an impact on the minority carrier lifetime of the silicon which ultimately affects conductivity of the switch in the ON state. The doping applied to the wafer will also affect OFF state performance, as high levels of doping degrade switch isolation. The thickness of wafer is 530μm; this also influences the distribution of free carriers in the switch.

2) *Texturing*: The silicon surface was textured using an anisotropic etching process in Isopropyl Alcohol (IPA) and 10% NaOH solution at 90° for 15 minutes. This results in the creation of a random pyramid structure on the wafer's surface, where typically the pyramids have a base dimension of 4μm, figure 3. This process reduces surface reflection of the die

allowing more photons to enter the silicon, as shown in table II.

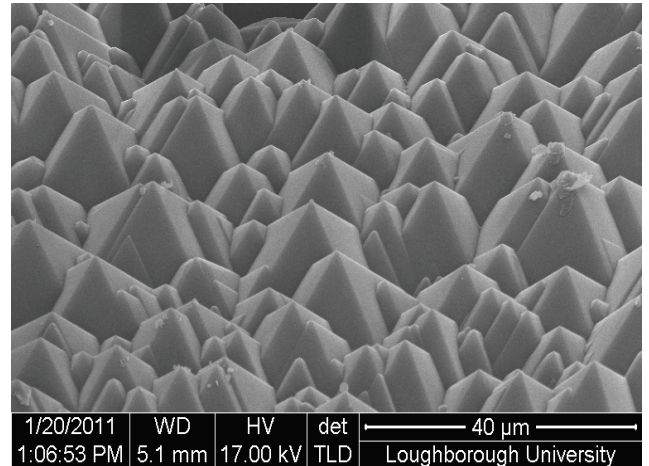


Fig. 3 Representative SEM of silicon surface for a sample which has undergone texturing

3) *Passivation*: A passivation layer to reduce the number of traps on the surface of the silicon, hence increasing minority carrier lifetime, was thermally grown on both polished and textured silicon samples. Silicon dioxide was deposited to a depth of 57nm (refractive index n=1.45). Optical properties such as thickness of the oxide and reflectivity of the samples were measured using spectrophotometer and ellipsometer, reflectivity is presented in figure 4(a).

Quasi-steady state photoconductance method was used to monitor the minority carrier lifetime. This value is affected by carrier concentration. Equation (1) relates carrier concentration, n, to conductivity, σ. As the silicon is near intrinsic, the density of holes and electrons is assumed to be equal. Electron and hole mobility μ<sub>h</sub> and μ<sub>e</sub> are respectively 1414 cm<sup>2</sup>V<sup>-1</sup>s<sup>-1</sup> and 471 cm<sup>2</sup>V<sup>-1</sup>s<sup>-1</sup>, where q is the elementary charge constant. When σ is 45S/m as assumed in the parameter simulation study, the carrier concentration is 1.5×10<sup>15</sup>cm<sup>-3</sup>.

$$n = \frac{\sigma}{q \cdot (\mu_e + \mu_h)} \quad (1)$$

The carrier lifetimes presented in Table II are based on this carrier concentration for an undiced wafer.

4) *Dicing*: The samples were diced into 1mm × 1mm switches using a diamond wafer saw – this process reduces the carrier lifetime as the saw creates defects at the dice edges. Defects can be reduced by polishing the edges after dicing, but these facilities were not available for this initial study. The silicon was attached to the optimised transmission line design using silver epoxy and mounted on a metal base to act as a ground plane and allow attachment of SMA connectors.

#### B. Measurement

A laser diode coupled to a 1mm diameter fibre optic cable delivered 200mW of optical power to the silicon die to allow switch control, as described by Panagumwa *et al.* [1]. S-

Parameter measurements were taken using the Anritsu 37397D Vector Network Analyser, figure 4 (b) and (c). It is assumed that all light that is not reflected is absorbed by the silicon, this is a valid assumption as the depth of the silicon is  $530\mu\text{m}$ ; using a laser with a wavelength of  $980\text{nm}$  the absorption coefficient is  $\sim 100\text{cm}^{-1}$  and hence very little light is transmitted through the silicon.

#### IV. RESULTS AND DISCUSSION

The results indicate that treating the silicon has minor effect on the OFF state characteristics of the switch, and hence only ON state insertion loss changes will be discussed. Reflection values throughout the optical and near IR spectrum are presented in figure 4(a), however quoted reflection percentages refer to  $980\text{nm}$  in the text. Insertion loss values are compared at  $2\text{GHz}$  throughout.

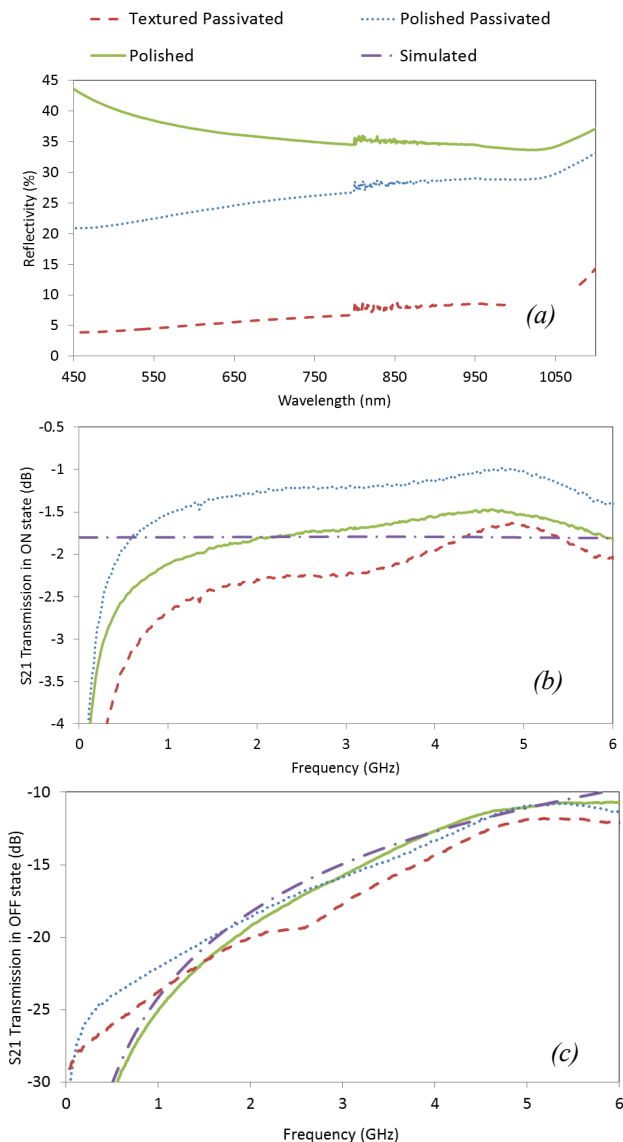


Fig. 4 (a) reflectivity results, (b) transmission results in the ON state (c) transmission results in the OFF state

Simply passivating the silicon sample reduces the insertion loss of the photoconductive switch by  $0.5\text{dB}$  from  $1.8\text{dB}$  to  $1.3\text{dB}$ , which in terms of power ratio is a 13% improvement, figure 4(b). A small amount of this increase can be attributed to a reduction in reflectivity by 5.2%, however the bulk improvement in performance is due to the increased carrier lifetime of the silicon.

Polished silicon was measured to have a minority carrier lifetime of  $13.4\mu\text{s}$ , compared to passivated silicon which has a minority carrier lifetime of  $36.6\mu\text{s}$ . The carrier lifetime has been improved through eliminating dangling surface bonds using oxygen. Silicon atoms bond with the oxygen and hence reduce traps which cause carriers to recombine. Since carriers are available for longer, conductivity is improved and hence insertion loss is reduced.

The measurement results indicate that texturing the surface of the silicon does not improve microwave performance in terms of insertion loss. There are more photons entering the textured passivated silicon, a reduction in reflectivity of 20.4% is observed when compared to the passivated polished sample. However the insertion loss is increased by the texturing process from  $1.3\text{dB}$  to  $2.3\text{dB}$ , equating to 21% increase in loss.

There are a number of possible reasons for this degradation. The texturing process physically changes the flat surface of the die and creates non uniform air gap cavities (depth  $\sim 4\mu\text{m}$ ) between the silicon surface and the copper transmission line it is in contact with.

Potentially, these cavities decrease capacitance and reduce coupling between die and transmission line, therefore increasing loss. Taking these cavities into account in the simulation model as a  $2\mu\text{m}$  air gap on the surface of the silicon it is clear that there is a reduction in insertion loss between the textured and non-textured switches at  $2\text{GHz}$ , figure 5.

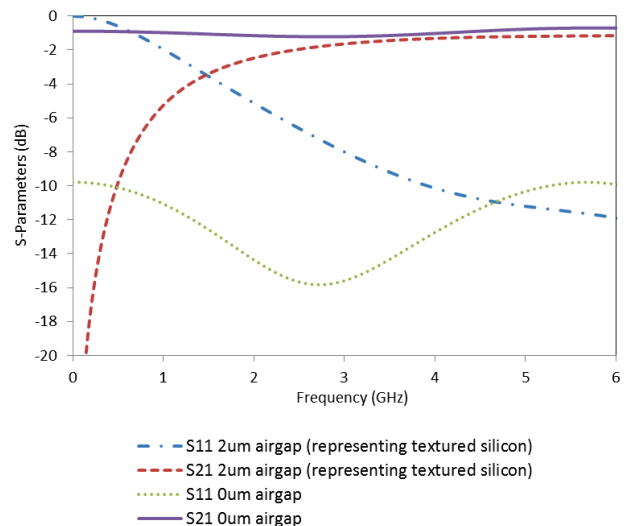


Fig. 5 Simulation result of a passivated silicon die on a transmission line, with and without a representative 'textured' airgap



A second point to consider is that texturing increases the surface area of the silicon and damages the surface compared with a polished finish. Despite passivation, the surface is still an area of high carrier recombination compared to the bulk of the silicon. There is a 7.1 $\mu$ s reduction of carrier lifetime of the passivated textured sample compared to the passivated polished sample.

Since there is a greater area for recombination of carriers to occur at the surface, this is most likely to be the main reason why the conductivity is reduced. The wafers used in this study are high quality FZ, whereas lower grade CZ silicon is typically used in the manufacture of solar cells where this texturing technique is normally applied. The observed degradation to microwave performance may be attributed partially to this fact as the damage caused to high grade FZ compared to CZ is not outweighed by the benefit of reduced light reflectance across a broader frequency spectrum.

## V. CONCLUSION

The switch has been optimised in two ways. Firstly, switch topology is altered to produce the best possible insertion loss without unacceptable degradation of isolation. This was achieved through choosing a substrate material that yields a transmission line width that matches the dimensions of the silicon die.

The resulting switch yields simulated S21 result of -1.79dB when ON and -18.5dB when OFF. This optimised configuration was then used as a base to explore different techniques to maximise the number of carriers generated by enhancing light coupling and reducing the recombination rate by removing surface defects.

Passivation using silicon dioxide increases the minority carrier lifetime of the silicon by a factor of 2.7 hence reducing insertion loss from 1.8dB to 1.3dB. The addition of texturing, increases light absorption but does not improve microwave performance due to the possible effect this process has on recombination velocity of the carriers and also the increase in air gap created between the silicon and copper transmission line by the pyramid structure.

## VI. FUTURE WORK

Anti-reflection coating (ARC) can reduce reflection of light for a given wavelength, the use of Silicon Nitride and

Aluminium Nitride are commonly used to increase illumination entering solar cells.

In addition, it may be possible that texturing could improve performance of the switch if a pulsed light source emitting a broad spectrum of light is used. Texturing gives the benefit of reducing reflection at all wavelengths of light as opposed to ARC which is targeted to a specific wavelength. If the silicon die was only textured on the surface exposed to illumination, the air gap cavities could be avoided, potentially improving microwave performance.

## ACKNOWLEDGEMENTS

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