Picosecond Photoresponse in Polycrystalline Silicon

The OMEGA laser driver line currently incorporates silicon (Si) photoconductive switches as part of the electro-optic pulse-shaping system. These switches conceptually serve two functions: (1) to generate an electrical square pulse with a sharp leading and trailing edge, when illuminated by a short optical pulse;[1] (2) to appropriately direct a broadband (0.1- to 10-GHz) shaped electrical pulse to the Mach–Zehnder integrated-optic modulator. The operating characteristics of the switches are optimized by minimizing the rise and fall times of the generated electrical square pulse and by maximizing the bandwidth of the directed broadband electrical shaped pulse.[2] Because the performance requirements of photoconductive switches in OMEGA pulse shaping are stringent and sometimes conflicting, a thorough exploration of the silicon photoconductive process is important.

In this article we address the generation of laser-pulse–induced electrical transients with short rise times, using silicon photoconductive switches. Related aspects of photoconductive switching, such as response at different laser wavelengths and Si integrated-circuit compatibility, are considered. We also explore the optimization of electrical pulse generation by probing the intrinsic limits of the Si and polycrystalline Si (polySi) material. In the 1980s Auston[3] and others studied processing methods to reduce the Si intrinsic photoresponse time far below the microsecond limit set by its free-carrier lifetime. Although very fast responses were generated, the temporal resolution of the measurement equipment at that time was not sufficient to directly resolve the rise and fall times of the resulting photoresponse. To circumvent this measurement bandwidth limitation, optoelectronic correlation methods were developed.[4] Correlation takes advantage of the switch itself by using another, similarly fast photoconductive switch in a pulser/sampler configuration. The measured response from the sampler is then a correlation of the two switch responses. This procedure, however, does not allow direct reconstruction of the switch response because, even if the switch geometries are identical, the measured response is not equivalent to a true autocorrelation since the electric fields across the gaps have different time evolutions. This is important because many parameters of the photoconductive switches, such as carrier mobility and trapping, vary with the applied electric field strength. Therefore, detailed knowledge of the Si photoresponse and how it depends on the switch bias and illumination for different Si process conditions could not be determined.

We have measured the Si switch response at 800 nm and at the typical communication wavelength of 1.55 μm, using a 34-GHz sampling oscilloscope to quickly and easily measure properties dependent on charge (current integral) effects, such as quantum efficiency and saturation. We have also used an electro-optic (EO) sampling system capable of measuring submillivolt and subpicosecond responses.[5] This allowed direct observation of the Si photoresponse rise and fall times.

Sample Preparation and Characterization

The tested samples were 2.3-μm-thick, 2 × 2-mm, low-pressure chemical-vapor–deposited (LPCVD) films of polySi grown at a substrate temperature of 600°C in 200 mTorr of silane. A 1-μm-thick multilayer of metal was evaporated onto the polySi in an interdigitated fashion. The top layer was Au for solderability, while the bottom layer was Al for good adhesion to Si and to promote ohmic-like contacts. The samples were not annealed, and no implantation or etching was performed. Instead of growing the film on a silicon substrate with an oxide insulating layer, we used a fused silica substrate to facilitate switch illumination. This optimized the oscilloscope test fixture bandwidth because the sample could be directly soldered in a flip-chip manner across a microstrip gap, eliminating bandwidth-limiting discontinuities such as inductive wire-bond leads. Illuminating the sample from the back side (through the silica) also leads to reflection of the incident laser illumination from the top metal contacts, increasing rather than decreasing the number of photons absorbed, as front-side illumination would have done.

For characterization purposes, the polySi surface was etched preferentially at the grain boundaries, and a scanning electron microscope (SEM) image taken of the surface (see Fig. 71.29) revealed a polygrain size of approximately 30 nm. A sample

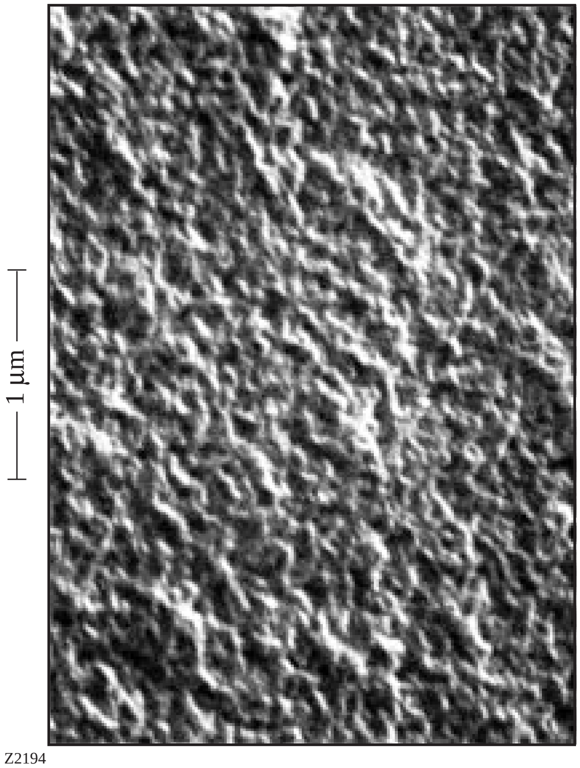

Figure 71.29
An SEM image of the polySi surface taken after preferential etching at grain boundaries reveals grain sizes of the order of 30 nm.

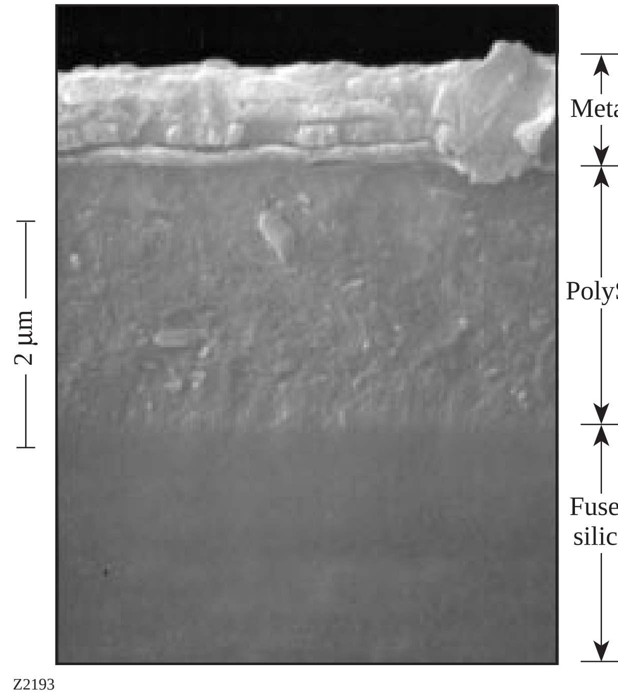

Figure 71.30
An SEM cross-section image showing the metal multilayer on the 2.3-μm polySi layer.

was also cleaved, and a 4-nm conductive silver layer was evaporated onto the exposed face, allowing a high-resolution SEM photograph of the switch cross section to be taken (see Fig. 71.30). The image shows the silica substrate beneath the 2.3-μm layer of polySi; on the top is a multilayer of metal that allows a robust, repeatable low-temperature-solder contact between the polySi and the microstrip transmission line. Close inspection of the grown polySi layer reveals some evidence of columnarity in the growth direction of the Si grains, which is not unexpected; however, the measurements were not significantly affected since the current flow was primarily in the direction normal to the silicon growth.

To independently confirm the polySi grain size and obtain preliminary data on absorption depth, a Perkin–Elmer Lambda 9 spectrophotometer was used to measure the transmission of the polySi-on-silica sample (see Fig. 71.31). The data, corrected for thin-film etalon fringes, show a broadened absorption band edge and a small but measurable amount of absorption in the energy bandgap, which is consistent with the small-grain microcrystalline film morphology observed in the SEM.

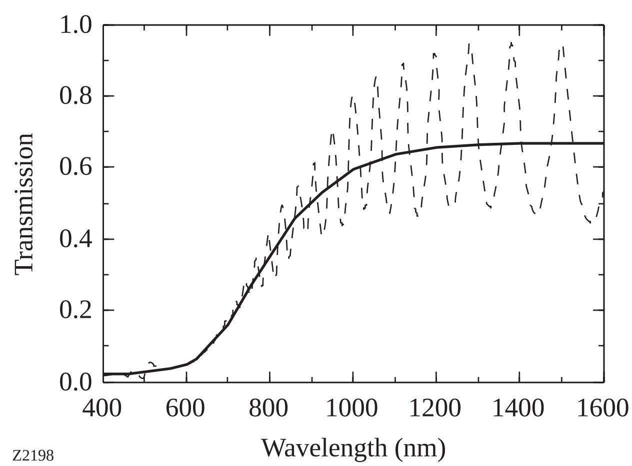

Figure 71.31
Transmission spectra of the polySi sample (solid line), corrected for thin-film etalon effects (dashed line).

Measurement and Experimental Results

A 34-GHz (10-ps intrinsic rise time) sampling oscilloscope measurement setup, shown in Fig. 71.32, allowed convenient measurement of relative quantum efficiencies for various laser wavelengths, since our EO sampling system operated up to only near-infrared wavelengths and did not extend into the fiber optic communication wavelengths. The oscilloscope measurements also permitted convenient testing of the switch signal's dependence on voltage bias (Fig. 71.33) and illumination power (Fig. 71.34). These two plots, taken at a laser wavelength of 800 nm, show that the switch response is linear with both the voltage bias and incident laser fluence, indicating that the switch was not saturated. Additionally, the pulse-width dependence (Fig. 71.35) on bias voltage was nearly nonexistent, indicating that the photoresponse time was not due to carrier sweep-out but limited by either the free-carrier lifetime or the RC time constant of the switch. Since, as we will demonstrate later, EO sampling measurements show that the material response is in the 3-ps range, we can conclude that the observed photoresponse of our polySi switch is limited by the switch interdigitated geometry and the switch fixture RC time constant.

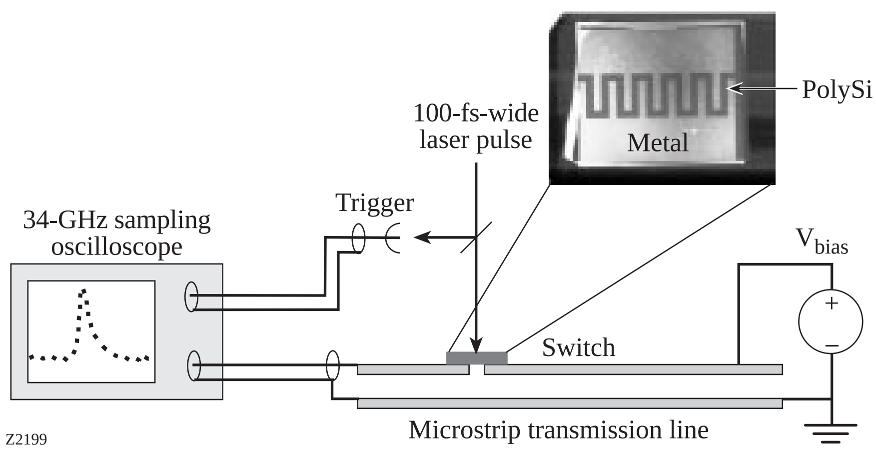

Figure 71.32
Sampling oscilloscope measurement setup. Inset shows the interdigitated switch geometry. Switch dimension is 2 mm × 2 mm; finger separation as well as finger width is 100 μm.

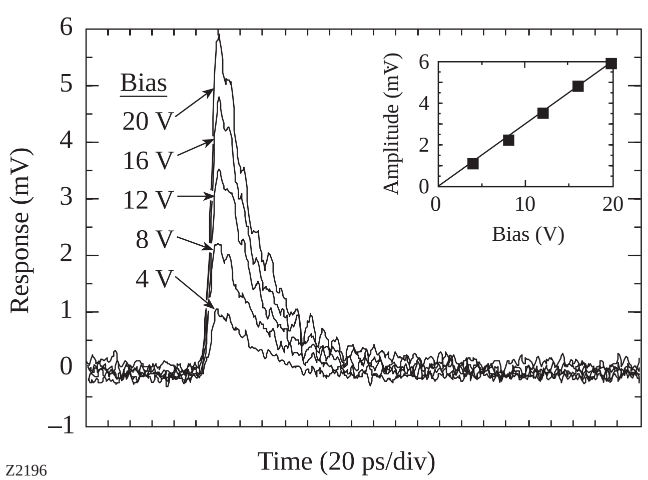

Figure 71.33
The photoresponse at 800-nm illumination wavelength measured for different switch bias levels. The inset plots a linear dependence on gap voltage bias.

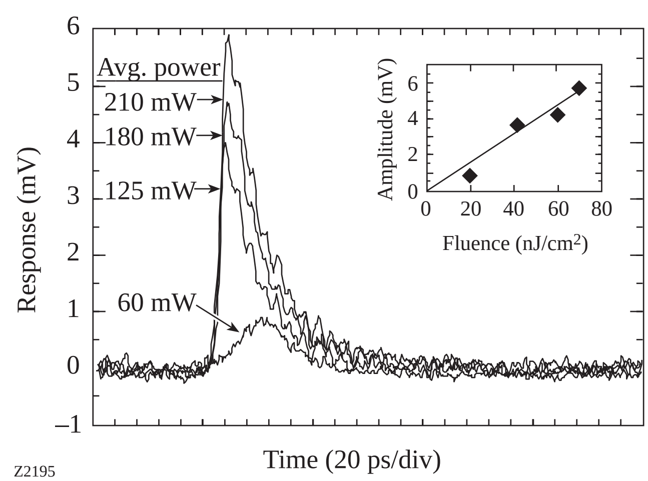

Figure 71.34
The photoresponse at 800-nm illumination wavelength measured for different pulse average-power levels. The inset shows linear response versus illumination fluence.

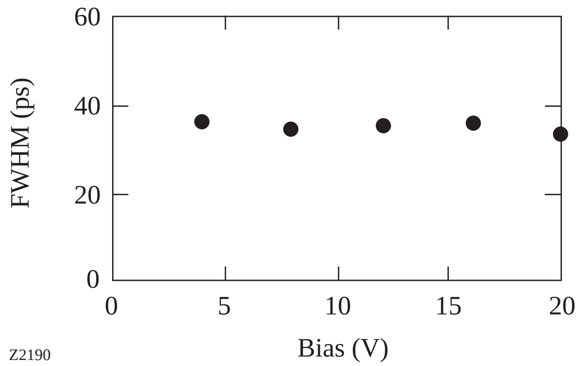

Figure 71.35
The photoresponse FWHM at 800-nm wavelength and 40-nJ/cm^2 fluence versus the switch bias.

An optical parametric amplifier (OPA) pumped by an 810-nm regenerative amplifier and a white-light continuum system at 1-kHz repetition rate were used to measure the response at 1.55 μm. Since our switch was not processed to improve its subband absorption characteristics, the quantum efficiency of the device in the infrared was less than 10^{-4}. We were able, however, to observe a response at 1.55 μm (Fig. 71.36), which was again a switch-limited signal of 36-ps full-width at half-maximum (FWHM). This result indicates that with suitable efficiency improvement, a high-speed, monolithic, all-silicon, optoelectronic integrated circuit is feasible, using, for example, porous silicon[6] as the transmitter and a type of polySi material for the detector.

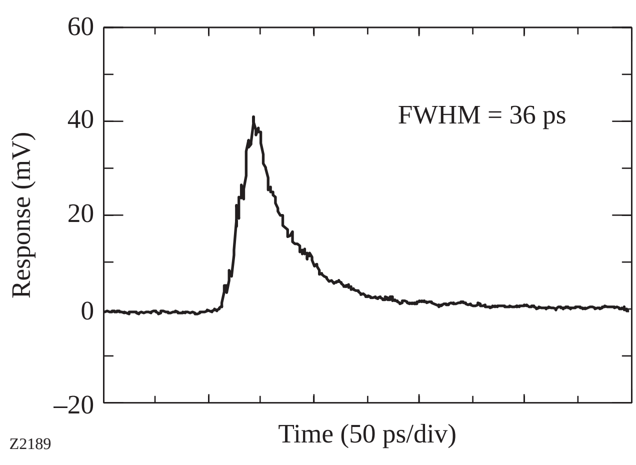

Figure 71.36
The photoresponse at 1.55-μm illumination wavelength. The quantum efficiency was less than 10^{-4}.

Our switch configuration was not designed for EO measurements.[5] Nevertheless, we managed to get preliminary results by connecting the switch as a meander-type slot line. The signal was generated and measured entirely on the face of the switch structure. It propagated in a meander line fashion along the gap from one end of the switch to the other. The transient measured before entering the first bend is shown in Fig. 71.37. We note a subpicosecond (system-limited) rise time, followed by a decay with an initial fall time of approximately 3 ps.

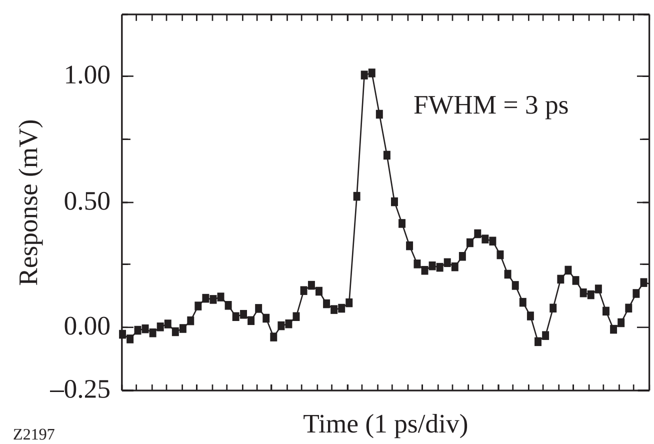

Figure 71.37
Electro-optically measured signal from a polySi switch connected as a meander-type slot line.

Conclusions

A standard fabrication technique was implemented to design small-grain polySi photoconductive switches fully compatible with Si VLSI processing. By means of EO sampling, a material photoresponse of 3-ps FWHM was observed. The switch responded to 800 nm and 1.55-μm femtosecond laser illumination with switch-geometry–limited photocurrent pulses shorter than 40-ps FWHM. The far-infrared response time was generated in nonimplanted silicon with ohmic-like metal-semiconductor contacts, indicating the response was limited by the relaxation time of the extended-state (free) carriers into localized (nonmobile) states. Our preliminary measurements of response time and efficiency can be optimized using simple process changes such as annealing at moderate temperatures, sputter-etching for surface damage, or Fe and Au deep-level defect doping, while still allowing the switch to be integrated with Si IC's.

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