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Inhibition of surface-related electrical breakdown of long p^+-i-n^+ silicon structures

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Semiconductors such as silicon and GaAs appear attractive for use in high voltage devices because of their high bulk dielectric strength. Typically, however, such devices fail at a voltage well below that expected due to a poorly understood, surface-related breakdown process. In this letter we present empirical results which show that such breakdown of long silicon p^+-i-n^+ devices can be inhibited by the application of weak visible or near-infrared illumination. These results suggest a technique for avoiding surface flashover in practical high voltage devices, and provide information about the physical mechanisms responsible for initiating flashover.

There has recently been considerable interest in the application of semiconductors to high voltage photoconductive switching technology.[1–4] The utility of these devices is severely limited, however, by the occurrence in the nonilluminated, hold-off state of electrical breakdown at average applied fields much less than the bulk breakdown field of the semiconductor.[5–13] This problem has hampered the development of high voltage solid state devices for more than 30 years,[14] and the physical basis for the breakdown phenomenon is still not well understood.

Visible emission is frequently observed during such an event. In analogy with breakdown of insulators, the phenomenon has been termed "surface flashover." We have previously presented empirical results which showed that the current during such breakdown of nonilluminated, forward-biased, 1 cm long, p^+-i-n^+ silicon devices in a vacuum ambient is carried inside the surface.[6,10,12] For this reason, the term surface flashover is a misnomer when applied to this phenomenon, and in this letter we will use the term "breakdown." In this letter we present experimental results which demonstrate that the occurrence of such a breakdown in these devices can be inhibited by illuminating the cathode region with weak infrared or visible light just prior to or coincident with the application of voltage to the device. Our finding has significant technological importance in that it offers a practical method for increasing the voltage rating of silicon p^+-i-n^+ photoconductive switches. The illumination does increase the dark current of such a switch slightly, but for most applications the effect would be insignificant.

For all results reported here the samples were rectangular prisms of weakly n-type silicon with typical dimensions of $10\times7\times2$ mm and resistivity as measured by a four-point probe of 1.3–1.6 kΩ cm. After cutting and grinding, the faces of all samples were chemomechanically polished using a standard colloidal silica solution and etched in HF to remove oxides. This treatment produced flat, mirrorlike surfaces which should be relatively damage-free. Electrical contacts were made by diffusing boron and phosphorus impurities into the opposite 7×2 mm faces to make a p^+-i-n^+ structure with an intrinsic region 10 mm long. To make external contact, films of 2500 Å of aluminum and 5000 Å of copper were thermally evaporated onto these faces. Finally, the sample was indium soldered to steel buttons.

Pulsed, current-voltage curves obtained from the mounted samples without illumination were diodelike. In the forward direction, the curve was nearly linear with the slope corresponding to the measured silicon resistivity of about 1.4 kΩ cm. Using 1 ms voltage pulses, the forward current was typically about 175 mA at 800 V, varying little between samples. The reverse current varied substantially between samples and ranged from 0.5 to 5 mA at -800 V.

Figure 1 shows the experimental setup. The system used a nitrogen-laser-triggered spark gap which generated a rectangular 30 kV voltage pulse of duration 280 ns, with rise and fall times of about 15 ns. The voltage polarity forward-biased the diode. This voltage pulse was applied across the long (10 mm) dimension of a sample mounted inside a vacuum chamber evacuated to a pressure less than 10^{-6} Torr. The attenuated output of a Q-switched Nd:YAG laser was used to probe the effects of 532 and 1064 nm illumination on the breakdown. The relative timing between the illumination pulse and the voltage pulse was controlled with a delay generator. Voltage traces were obtained with a Tektronix 7104 oscilloscope, and the

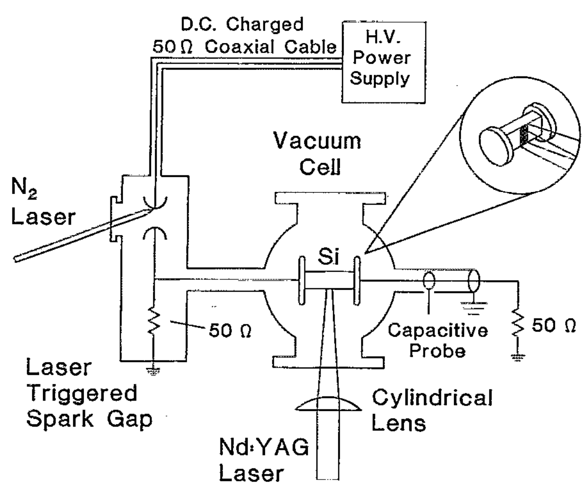

FIG. 1. Schematic of the experimental setup. Inset shows detailed isometric view of the illuminated region (shown cross-hatched) on the front surface of the sample.

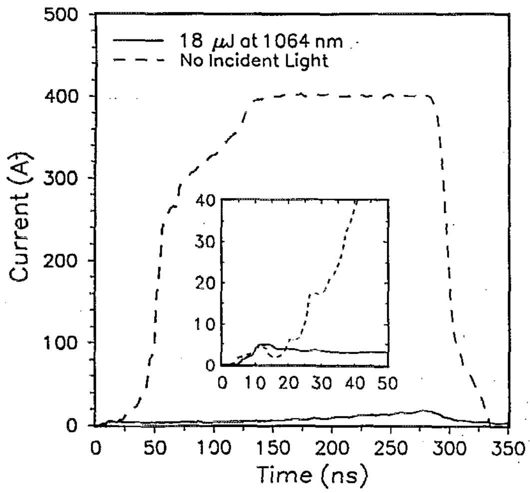

FIG. 2. Plot of current as a function of time through a silicon sample. Dashed traces represent a typical breakdown event with no light incident on the sample. Solid traces show the current when a 1 mm long region adjacent to the cathode contact was illuminated with a 10 ns, 18 μJ pulse of 1064 nm light applied 120 ns before the voltage pulse. The inset graph shows the behavior at early times on an expanded scale.

probe-limited rise time of the system was less than 3 ns.

Optical access to the front and back of the sample was provided by windows on opposite sides of the vacuum chamber. The sample was mounted such that the largest faces (10×7 mm) of the sample were parallel to the two windows. In separate experiments, both the 1064 nm fundamental and the 532 nm second harmonic of the Nd:YAG laser were used to illuminate the front face of the sample only. The attenuated and homogenized laser beam was shaped to produce an illuminated bar on the sample surface which extended across the full 7 mm width. The fractional span and position of the bar along the 10 mm length of the sample could be varied. The inset isometric view in Fig. 1 shows graphically how the sample was illuminated. The temporal width of the pulses was about 10 ns.

The breakdown inhibiting effect of weak illumination is shown in Fig. 2. The dashed curves show sample current as a function of time without illumination, and the solid curves show similar information, but for the case in which an 18 μJ pulse of 1064 nm light illuminated the region near the cathode just prior to the arrival of the voltage pulse. The inset in Fig. 2 shows the same data on an expanded scale. Without illumination, breakdown is initiated within about 20 ns, and the current rises to a circuit-limited 400 A within about 100 ns. With illumination, on the other hand, breakdown does not occur. Instead, the current increases slowly, reaching a final value of about 15 A at the end of the voltage pulse. The data shown in Fig. 2 are typical of those seen with several other samples. We emphasize that for both curves, the switch is intended to be in the off state. For the dashed curve breakdown occurred, effectively closing the switch. For the solid curve, breakdown did not occur and the switch remained effectively off, although the current did rise slowly. For the optimum conditions a minimum of about 10 μJ of 1064 nm illumination was required to suppress breakdown during our 280 ns voltage pulse. This illumination increased the "dark current" of the device from about 2 to about 3 A.

Another set of experiments showed that the illumination is most effective in inhibiting breakdown when applied to the cathode region. In these experiments we varied the position and size of the illuminated region. The data shown in Fig. 2 were generated by illuminating a strip extending out from the cathode about 1 mm. When the strip of illumination was moved away from the cathode along the length of the sample, the light became less effective at inhibiting the breakdown, and within 1–2 mm of the anode the light no longer delayed breakdown at all. Fixing the position near the cathode and varying the span of the strip from less than 1 mm up to 4 mm had little effect.

Still another set of experiments showed that the photocarriers produced by the illumination play an important role in breakdown inhibition. In these experiments the laser pulse was applied to a 1 mm wide strip just in front of the cathode contact at varied times relative to the voltage pulse. When the laser illumination was applied before the voltage pulse, we found that the light inhibited or delayed breakdown when the difference between the two pulses was less than about 20 μs, comparable to the measured minority carrier lifetime of about 5 μs in these samples. The photoinduced current also decreased with increasing delay. Breakdown could be inhibited when the light pulse was applied after the arrival of the voltage pulse, but only if the light arrived before the sudden current rise signaling the onset of breakdown. Once breakdown began we saw no cases in which the process was reversed by the application of light.

Results of experiments with light at 532 nm were generally similar to those at 1064 nm, except the energy threshold required to inhibit breakdown was about a factor of 10 higher. We also found that even unfocused light from a simple 40 W incandescent table lamp placed about 4 in. from the sample was effective in inhibiting the breakdown.

These results are of considerable technological interest because they offer a method for increasing the voltage rating of p^{+}-i-n^{+} devices. It seems feasible to incorporate a small incandescent bulb built into a silicon photoswitch to inhibit breakdown. The question of the physical mechanism responsible for the breakdown inhibition remains, however. The principal effect of the weak illumination is the generation of free carriers in a surface layer about one absorption length thick. Assuming 10% of the 18 μJ, 1064 nm light pulse is absorbed to create free photocarriers, about 10^{13} free electrons and holes would be produced, resulting in a roughly uniform plasma with density about 10^{15} cm^{-3} and a Debye length of about 10^{-6} cm. With 532 nm illumination a much denser plasma is produced in a ~ 1 μm thick surface layer. Our observation that breakdown can be inhibited by a light pulse appearing at the sample only within a few minority carrier recombination times of the time of application of the voltage pulse implies that the photocarriers play a role in the inhibition of breakdown.

It is interesting that illuminating one face with 532 nm light inhibits breakdown on all four faces of the sample, even though photocarriers are produced only on the illuminated face. Inhibition must, apparently, be the result of some long range effect of the photocarriers, such as shielding of the electric field. The 532 nm illumination creates a high conductivity surface layer which is parallel with the bulk material under it. If the resistance of this layer is much less than that of the bulk, the layer tends to short out the applied field thereby reducing the field throughout the depth of the region. Neglecting density and surface effects on carrier mobility, assuming a thermal carrier density of $10^{12}\ cm^{-3}$ in the bulk and 3×10^{13} photocarriers produced in the surface layer through the absorption of 10 μJ of absorbed 532 nm radiation, the expected resistance of the surface layer is about 0.1% of that of the bulk, and substantial shielding is expected.

The results we report have interesting implications for both the basic and applied science aspects of semiconductor breakdown. From an engineering standpoint, the prospect of effectively increased holdoff voltage at the cost of a simple low-power light source is attractive. From a basic physics viewpoint, the ability to probe the characteristics of the breakdown process with a light pulse opens up a wide variety of diagnostic possibilities. The energy, pulse width, wavelength, spatial position, and application time of the pulse can all be varied to provide insight into the important processes occurring during breakdown on silicon.

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