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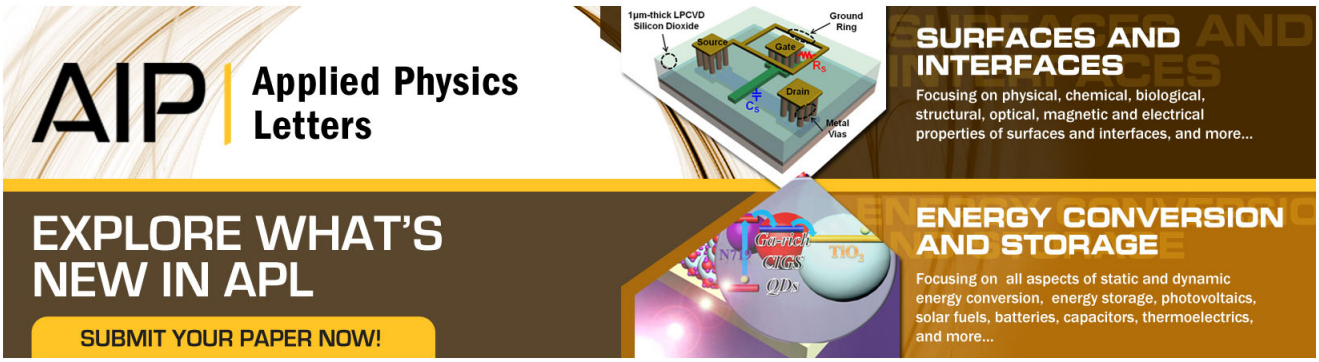

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F is lowest. The TSEE intensity here is lower than the intensity of the x-rayed area that was not exposed to laser light, suggesting that light-stimulated release of trapped electrons exceeded retrapping during the duration of the laser pulse. This may be expressed by $\beta n_c(N-n) < PFn$, where N is the density of the traps associated with the 120 °C peak of Fig. 1, n is the density of trapped electrons, n_c is that of free electrons, and β is the retrapping coefficient.[4] P is the absorption cross section for 1.06-μ photons. By absorbing a photon, electrons are released from the traps N and reach the conduction band.

At intermediate light fluxes (region II in Fig. 4), the TSEE intensity is much higher than the intensity of the original x-rayed area, indicating that additional electrons had been trapped during the laser pulse. Now we have $\beta n_c(N-n) > PFn$, which is of course possible only if the generation of photocarriers from donors increases faster with F than the release of trapped carriers does. A nonlinear dependence of photoconductivity on the light flux is well known in other materials, e.g., ruby.[5]

At the peak laser flux in the center (region III, Fig. 4), new processes occur. The concentration n_c of photocarriers becomes large enough, at laser power densities around the surface-damage threshold, that they are able to absorb large amounts of light energy, which is either quickly deposited to the lattice in the form of a "phonon shock wave" or which heats up the conduction electrons sufficiently to ionize filled traps by inelastic scattering.[5] In any case, traps that were filled up to this time are now completely emptied. Our experiments indicate that the threshold laser flux required for the occurrence of the dark center spot is only a fraction (typically $\frac{1}{5}-\frac{1}{2}$) of the laser surface-damage threshold.

The appearance of a dark center spot in the TSEE image is, therefore, an indication that the peak laser power density is approaching the surface-damage threshold.

The experiments described above suggest that the TSEE-imaging technique be applied to nondestructive testing of optical surfaces with respect to their susceptibility to laser damage.

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Peak Voltage of the Pyroelectric Response to Short Infrared Laser Pulses

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The peak voltage of the response in a pyroelectric sample to ir signals much shorter than the thermal and electronic time constants of the sample is shown to be proportional to the energy absorbed per signal, and independent of load resistance and signal repetition frequency, as long as temperature is far enough from the Curie point. These results were checked experimentally in triglycine sulphate and strontium-barium niobate.

Consider a pyroelectric (PE) sample with thermal and electronic time constants[1] $\tau_T = C_T/G_T$ and $\tau_e = RC$, C_T being the thermal capacitance of the sample, G_T is its thermal conductivity to ambient, R and C are the resistance and capacitance of sample and circuitry at preamplifier input. The sample temperature is far enough from the Curie point, so that all these values remain constant under small changes of temperature and voltage. Let a train of short ir signals of duration $T_1 \ll \tau_T$, τ_e and intervals $T \gg T_1$ be absorbed uniformly in the sample. If T does not exceed τ_T, the mean sample temperature $\overline{T}$ may be rising, but after a certain number of pulses a steady state is achieved in which $\overline{T}$ remains constant. Due to absorption of energy E_a per signal, at the beginning of each period the sample temperature will rise suddenly by E_a/C_T above the level at the ends of the periods. This will cause an abrupt rise of the PE voltage from its level at the ends of the periods by a peak value V_0,

$$V_0 = \xi E_a C_s / AC. \tag{1}$$

Here $\xi \equiv \lambda/\epsilon c$ is a material constant,[2] $\lambda = dP_s/dT$ being the PE coefficient, with P_s as the spontaneous polarization vector, ϵ is the permittivity, and c is the volume specific heat of the material. A is the electroded area, and C_s is the capacitance of the sample.

V_0 is seen to be proportional to the energy absorbed per unit area per pulse, and independent of R. It also does not depend on the pulse-repetition frequency f, $f \equiv 1/T$, as long as $\overline{T}$ remains far enough from the Curie point.

The PE responses have been studied at room temperature on six triglycine sulphate (TGS) and three strontium-barium niobate (SBN) samples, 10—40 μm thick, with major faces perpendicular to the polar axis.[2] The ir source was a CO_2 laser (wavelength 10.6 μm) with a power meter. Interchangeable load resistors R_L were connected parallel to the sample and to a simple FET source-follower circuit.[2] R_L was always much smaller than the resistance of the sample ($\sim 10^{13}$ Ω), so that $R = R_L$. The output voltages were led to a CRO.

The measured values of V_0 were proportional to E_a/A in all samples in a wide energy range starting from 10^{-11} J/cm^2 per pulse, with signal widths of 1 μsec to 4 msec. For low f and single pulses the linearity could be

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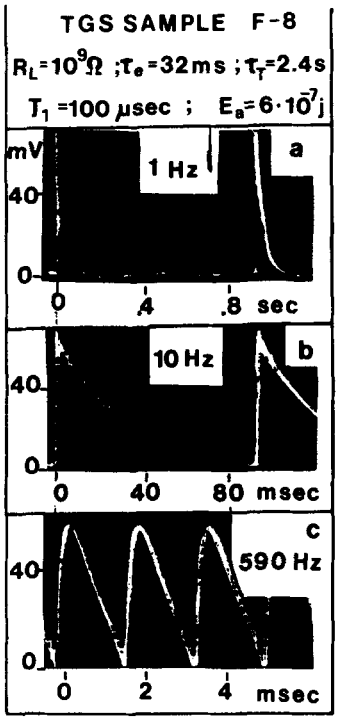

FIG. 1. Oscillograms of PE voltage response in a TGS sample ($A=3.2$ mm^2) at different signal repetition frequencies.

observed up to 10^{-3} J/cm^2. In order not to raise $\bar{T}$ by more than a safe 10 °C above ambient, with $f=300$ Hz the range was limited to 10^{-4} J/cm^2 per pulse, and with $f=7.2$ kHz to 4×10^{-6} J/cm^2 (in TGS; in SBN the energies could be increased by a factor of 2). Values of V_0, calculated from Eq. (1) using[2] $\xi=4600$ cm^2/C for TGS and 630 cm^2/C for SBN and neglecting any temperature

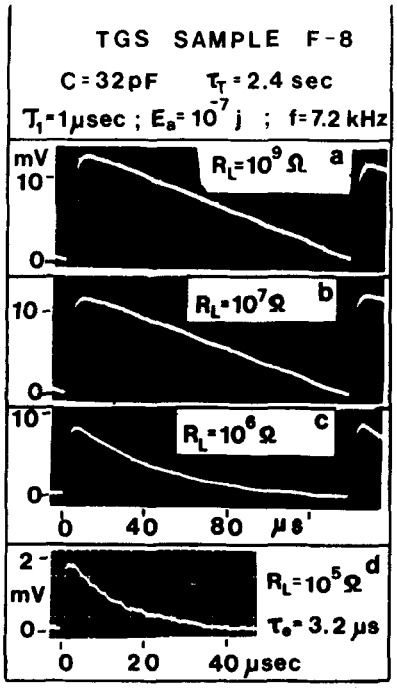

FIG. 2. Oscillograms of PE voltage response to Q-switched laser signals in a TGS sample with different load resistors.

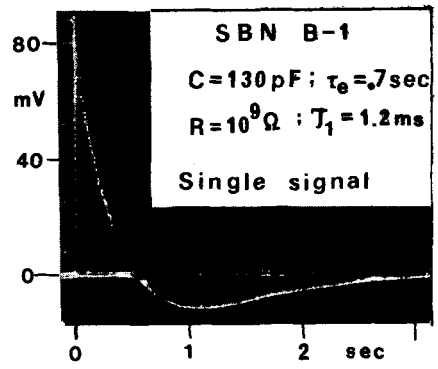

FIG. 3. PE voltage response to a single ir signal in a SBN sample ($A=0.5$ mm^2, $E_a=8\times10^{-7}$ J).

or frequency dependence of the material and sample parameters, were in agreement with the measured values within a factor of 2.

That V_0 remains constant under an almost four-order-of-magnitude change in f is shown by the oscillograms of Fig. 1. Here a TGS sample (F-8) with $R_L=10^9$ absorbs from each 100-μsec-wide ir signal an energy of 6×10^{-7} J. The peak voltage is ~65 mV with 1, 10 as well as with 590 signal/sec. (Note that the conditions $T_1\ll\tau_T$, τ_e and $T_1\ll T$ hold.)

The dependence of V_0 on R_L is illustrated in Fig. 2. Sample F-8 absorbs here 10^{-7} J from each 1-μsec-wide Q-switched laser pulse, while $f=7.2$ kHz. V_0 is seen to be ~12 mV for $R_L=10^7\ \Omega$ as well as $10^9\ \Omega$ (the same V_0 is obtained even with $10^{11}\ \Omega$). With $10^6\ \Omega$, V_0 is only slightly decreased (9 mV). However, $R_L=10^5$ makes $\tau_e=3.2\ \mu$sec, which is close to T_1; the short-signal condition does not hold, and V_0 is now smaller by a factor of 7 (and will continue to decrease proportionally to decreasing R_L).

Considering the peak-to-peak voltage V_{ptp} one should take into account that in the single-signal or low-f case, if R_L makes τ_e approach τ_T, the PE response has a shape[3] as shown in Fig. 3. When $\tau_e=\tau_T$ the undershoot of the response reaches a maximum[4] which is[5] $e^{-2}V_0\approx0.14V_0$. Thus, except for the low-f case, when an increase in R_L may cause an up to 14% increase in V_{ptp}, $V_{ptp}=V_0$ and does not depend on R_L, as long as the short-signal condition holds.

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