Table I. Gravitationally induced voltage differences $V_G$ between vertical, 91.4-cm high samples of metals *A* and *B*. $V_G$ in each case is an average of 10 to 20 readings.

| Metal *A* | Metal *B* | $V_G$ ($10^{-10}$ V) | Standard deviation ($10^{-10}$ V) | Vertical ion concentration gradient relative to copper rod Metal *A* | Metal *B* |
|---|---|---|---|---|---|
| Copper rod | Copper wire (not self-supporting) | +3.1 | 7.6 | 1.00 | 0.0 |
| Copper rod | Lead wire | −5.2 | 8.8 | 1.00 | 26. |
| Copper rod | Aluminum rod | −4.1 | 5.7 | 1.00 | 0.76 |
| Copper rod | Indium wire | +2.6 | 1.5 | 1.00 | 18. |
| Copper rod | Beryllium wire | −2.1 | 3.7 | 1.00 | 0.054 |
| Copper rod | Tungsten rod | −0.3 | 6.0 | 1.00 | 0.093 |
| Beryllium wire | Lead wire | −3.0 | 4.8 | 0.054 | 26. |
| Tungsten rod | Aluminum rod | +1.8 | 2.8 | 0.93 | 0.76 |

tal have opposite effects on its work function. The results are summarized in Table I. In all cases $|V_G|$ was less than $6\times10^{-10}$ V. Most values were zero within the standard deviation of the measurements.

Reference 4 predicts a field of $10^{-7}$ V/m outside a copper rod. Reference 6 states that this field should be proportional to the ion mass, the electron number density, the Fermi energy, and inversely proportional to Young's modulus. The ratio of ion mass to Young's modulus is proportional to the positive-ion-concentration gradient in a vertical self-supporting rod and is the most significant variable in the theory presented in Refs. 4 and 6. As shown in Table I this ratio varied by a factor of over 400 in the combinations of metals studied. Furthermore, in the comparison of the copper rod and the limp copper wire the full gravitationally induced voltage of $10^{-7}$ V should have appeared between the unconnected ends of the rod and wire, since the wire could not have had a gravity induced density gradient.

We conclude that the gravitationally induced electric fields outside metal surfaces are the same regardless of composition to within $\pm10^{-9}$ V/m. This result is in agreement with the theory of Schiff and Barnhill.[3]

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# THREE-PHOTON STEPWISE OPTICAL LIMITING IN SILICON

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Previously reported three-photon processes in solids have been concerned with a three-photon luminescence effect[1] and a three-photon photoelectric effect.[2] In this Letter we wish to report the observation and study of an intensity-dependent attenuation of 1.06-$\mu$ radiation in silicon at room temperature, which we believe is due to a stepwise absorption of three photons. This to our knowledge would be the first reporting of such a process in a semiconductor. Successful realization of multiphoton processes in solids is of interest from the point of view of obtaining information about the energy levels in these solids[3] and the possibility of using these solids as optical power limiters.

A block diagram illustrating our experimental arrangement is shown in Fig. 1. The source of 1.06-$\mu$ radiation was a continuously pumped Nd:YAlG (neodymium-doped yttrium aluminum garnet) $Q$-switched laser[4] which provided pulses of 1-kW peak power and 0.2-$\mu$sec duration at a repetition rate of 400/sec. The laser beam was focused within the sample by the 12-mm focal length, $f/4$ lens $L1$, and the transmitted beam was collected by the lens $L2$ onto the photocathode of photomultiplier $PM2$. $A1$ and $A2$ were properly calibrated optical attenuators; the former was used to vary the incident power and the latter to adjust the signal from detector $PM2$ equal to the signal from the monitoring photomultiplier $PM1$. Proper care was taken to make sure that $PM1$ and $PM2$ were not saturated, and each detector was provided with a narrow-band 1.06-$\mu$ interference filter. Single crystals of undoped as well as B- or P-doped silicon with resistivities of ~1000 to 25 $\Omega$ cm were used and the sample thickness varied between 0.05 and 0.2 cm. For low-temperature measurements the samples were mounted in a cold-finger Dewar with optical access windows. The observed dependence of transmitted intensity upon the incident 1.06-$\mu$ laser intensity is shown by the circled curve in Fig. 2 for a 0.05-cm thick sample of undoped silicon at 300°K. For laser fluxes below ~$5\times10^{27}$ photons/cm$^2$ sec the transmission curve is characteristic of a linear absorber. The actual low-level transmission measurements on a Beckman spectrophotometer yielded a value of 20 cm$^{-1}$ for the absorption coefficient $\alpha$ of undoped silicon at 1.06 $\mu$. However, for laser fluxes above ~$5\times10^{27}$ photons/cm$^2$ sec a limiting type of intensity-dependent attenuation was observed. It was found that the low-resistivity samples of Si doped with B or P behaved the same way as the undoped Si. At 77°K none of the samples exhibited any limiting behavior. Furthermore, a search for recombination radiation[5] from any of our samples under excitation with the 1.06-$\mu$ laser radiation failed.

Since no recombination radiation could be detected, our interpretation of the specific mechanism relies heavily on fitting the observed data with an appropriate transmission equation based on a kinetic analysis of the process. The

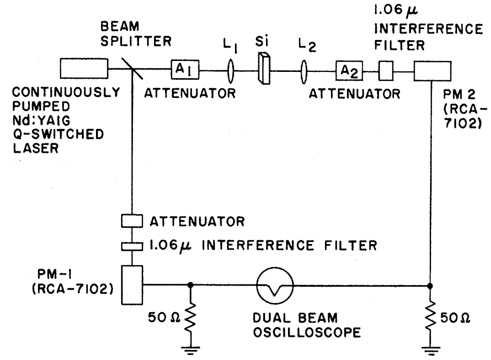


FIG. 1. Schematic of the experimental arrangement for measuring intensity-dependent attenuation.

indirect band gap[6] $E_g$ for Si is 1.07 eV, which is lower than the energy of 1.164 eV for the Nd:YAlG laser photons. The onset of the direct $\Gamma_{25}\rightarrow\Gamma_{15}$ transition occurs at approximately 2.3 eV and reaches its maxima at about 3.5 eV. These facts about the energy levels of Si suggest that the laser photons can be absorbed by a three-photon stepwise process via these transitions. Based upon the above-mentioned process, a steady-state solution of the appropriate rate equations yields the following expression for the change of laser intensity $I$ with thickness $x$ of the medium:

$$dI/dx = -[AI + BI^2 + CI^3]. \tag{1}$$

In Eq. (1) it is assumed that the intensities are well below saturation, and

$$A = nN\sigma_1, \tag{2}$$

$$B = nN\sigma\left[\frac{\sigma_2}{K_3} + \frac{\sigma_3 k_{41}}{K_3K_4} + \frac{\sigma_3 k_{42}}{K_3K_4} + \frac{\sigma_2}{K_4} + \frac{\sigma_2}{k_{21}} \pm \frac{\sigma_2 k_{31}}{k_{21}K_3}\right], \tag{3}$$

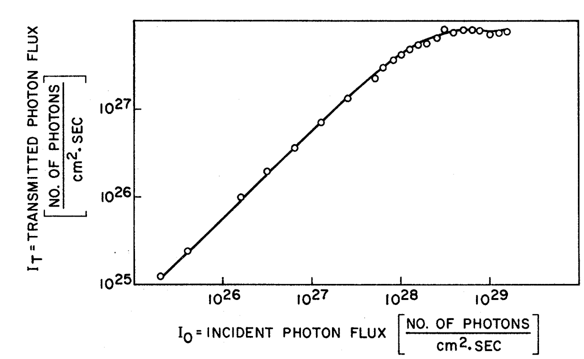


FIG. 2. Room-temperature dependence of transmission upon incident 1.06-$\mu$ laser flux for Si. The solid curve is calculated from Eq. (5) of the text. Values of the constants used are $A=108.5$ cm$^{-1}$, $B=7.5\times10^{-27}$ cm/sec, $C=3.4\times10^{-55}$ cm$^3$ sec$^2$, and $l=5\times10^{-3}$ cm.

and

$$C=n\sigma_1\sigma_2\sigma_3N\left[\frac{1}{k_{21}K_4}+\frac{1}{k_{21}K_3}+\frac{k_{31}}{k_{21}K_3K_4}+\frac{2k_{41}}{k_{21}K_3K_4}+\frac{k_{42}}{k_{21}K_3K_4}+\frac{1}{K_3K_4}\right]. \quad (4)$$

$N$ is the density of Si atoms, $\sigma_1$, $\sigma_2$, and $\sigma_3$ are the cross sections of each of the three single-photon steps, $n$ is the index of refraction, and $k$'s and $K$'s contain the decay constants of the states involved.

Integration of Eq. (1) yields the following transmission equation:

$$\frac{1}{2A}\left[\ln\frac{I^2}{I_0^{\,2}}-\ln\left(\frac{A+BI+CI^2}{A+BI_0+CI_0^{\,2}}\right)\right]-\frac{B}{A(4AC-B^2)^{1/2}}\left[\tan^{-1}\frac{B+2CI}{(4AC-B^2)^{1/2}}-\tan^{-1}\frac{B+2CI_0}{(4AC-B^2)^{1/2}}\right]=-l. \quad (5)$$

Equation (5) was fitted to our experimental data and the result is shown by the solid curve in Fig. 2. Using $l=5\times10^{-3}$ cm, $n=3.56$, $N=5.2\times10^{22}$ atoms/cm$^3$, the values of the constants which gave the best fit are $A=108.5$ cm$^{-1}$, $B=7.5\times10^{-27}$ cm sec, and $C=3.4\times10^{-55}$ cm$^3$ sec.$^2$ From Eq. (2) a value of $5.1\times10^{-22}$ cm$^2$ was determined for $\sigma_1$, which is in good agreement with the value of $3.9\times10^{-22}$ cm$^2$ obtained from the absorption coefficient measured with a spectrophotometer. In principle, it should be possible to determine $\sigma_2$ and $\sigma_3$ from Eqs. (2)-(4) provided that the decay constants are known; however, such data are not presently available on the decay constants.

With regard to other alternative processes, the possibility of either a simultaneous absorption of three laser photons or a double-photon process followed by a single-photon step was discounted on the basis of the fact that no limiting behavior was observed in Si at 77°K. A three-photon process consisting of a single-photon step followed by a double-photon process was also considered. For such a process, Eq. (1) for the change of laser intensity $I$ with thickness $x$ of the medium reduces to

$$dI/dx=-[AI+CI^3]. \quad (6)$$

However, using the measured value of absorption coefficient $\alpha=20$ cm$^{-1}$, the result of fitting the appropriate transmission equation obtained by solving Eq. (16) was very poor. Thus is is very unlikely that this alternative process is operative in Si.

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## ELECTRON-HOLE PAIR EFFECTS ON LANDAU LEVELS IN InSb

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Recently it has been shown that conduction-band Landau-level energies are drastically altered near certain critical magnetic field values by the presence of electron–LO-phonon interaction.[1] Such effects are in fact quite striking in InSb[2] even though the electron–LO-phonon coupling there is very weak.

In this Letter we suggest that electron-exciton interaction, the interaction which gives rise to electron screening associated with the high-frequency dielectric constant in semiconductors and insulators, should also produce in InSb large modification of Landau-level energies near critical field values.

Our argument is motivated by a paper of Toyozawa[3] in which the close analogy between the electron–LO-phonon interaction and the electron–Frenkel-exciton interaction is clearly