is selected from the agreement between the experimental data and the analytical curves.

It is found that the best fit is obtained by using Eq. (3) for $\alpha(E)$, with $2.0\times10^6 < E_i < 2.4\times10^6$ V/cm for both the 50 and 100-Ω cm samples. As mentioned in Sec. III, E_i is the crucial parameter, which determines the slopes of $(1/J)\,dJ/dt$-vs-$1/E_0$ curves.

We use $E_i = 2.2\times10^6$ V/cm as a best fit for both samples, with $\alpha_0 = 2.5\times10^7$ cm^{-1} for 50-Ω cm material and 5×10^7 cm^{-1} for 100-Ω cm material. This discrepancy[5] of a factor of 2 is not believed to be an inherent property of n-Si, but probably arises from the error limits (10%) on the absolute measurement of E_0.

The analytical fits are shown as solid lines in Fig. 6.

V. COMPARISON WITH THEORY AND WITH JUNCTION EXPERIMENTS

From a comparison with Baraff's theory of avalanche,[8] it is possible to obtain the values of the parameters entering the theory, namely, the electron-phonon mean free path λ, ionization energy $\mathscr{E}_i$, and the ratio of the scattering cross sections $r = \sigma_i/\sigma_r$, where σ_i is the ionization cross section and σ_r the phonon cross section.

To compare with the universal plots of Baraff,[8] it is necessary to express $\alpha(E)$ in the form $\alpha\lambda$ vs $\mathscr{E}_i/q\lambda E$. The procedure is to assume a value of $\mathscr{E}_i$, and then calculate $\lambda = \mathscr{E}_i/qE_i$. We then plot the experimental $\alpha\lambda$ vs $\mathscr{E}_i$, and then calculate $\lambda = \mathscr{E}_i/qE_i$. We then plot the experimental $\alpha\lambda$ vs $\mathscr{E}_i/q\lambda E$ for different $\mathscr{E}_i$ and compare with Baraff's universal curves. From such a comparison, it is found that it is possible to fit the slopes of the experimental curves for $\mathscr{E}_r/\mathscr{E}_i > 0.035$, where $\mathscr{E}_r$ is the optical phonon energy. This gives us one limit on $\mathscr{E}_i$. The magnitude of the $\alpha\lambda$ plot gives us another limit, $\mathscr{E}_r/\mathscr{E}_i <$ 0°05. Thus

$$0.035 < \mathscr{E}_r/\mathscr{E}_i < 0.05.$$

Using $\mathscr{E}_r = 0.061$ eV,[9] $1.2 < \mathscr{E}_i < 1.65$ eV, i.e.,

$$1.1\ \mathscr{E}_g < \mathscr{E}_i < 1.5\ \mathscr{E}_g,$$

where $\mathscr{E}_g$ is the energy gap in Si.

This result is in excellent agreement with the junction results of Lee *et al.*[10]

Using the above limits for $\mathscr{E}_i$, we obtain $60 < \lambda < 80$ Å, in agreement with Lee *et al.*,[10] but in disagreement with Ogawa's result[1,11] ($\lambda = 97$ Å).

The comparison with Lee's *et al.* and Ogawa's results is shown in Fig. 7.

The ratio r, which is very difficult to obtain from avalanche measurement[8] (because the $\alpha\lambda$ plot is very insensitive to r), can be adjusted to lie between 0.1 and 0.8. A more accurate way to determine r is to find the ratio of the mean free paths from photoemission experiments.[12]

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GaAs diode-pumped Nd : YAG laser

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Using a single chip heterostructure GaAs laser diode as a pump source, and temperature tuning its output wavelength to achieve a spectral overlap with the 8680-Å absorption line in Nd : YAG, lasting was observed in a 1.5-mm-diam ×25.4-mm-long laser rod. Pump light was directed through a special multilayer dielectric coating on one end of the laser crystal. This coating was designed to transmit 90% of the GaAs light, but still reflect internally 99.9% of the YAG laser light at 1.06 μ. The purpose of the end-pumping technique was to maximize the single-pass absorption of GaAs pump light by making the effective optical path within the laser rod as long as possible, thus compensating for the relatively weak absorption at 8680 Å in YAG laser crystals.

Most of the previously reported work with semiconductor-pumped YAG lasers (either with LED's or laser diodes) has involved side pumping of one form or another, using either the conventional ellipse[1,2] or direct-coupling techniques.[3,4] In either case, the longest optical path for the pump light was on the order of only a few millimeters, even if reflective coatings were used on the back side of the rod to produce at most two passes through the crystal along its diameter.

The layout of the end-pumping experiment is shown in Fig. 1. A Nd :YAG laser crystal having polished sides

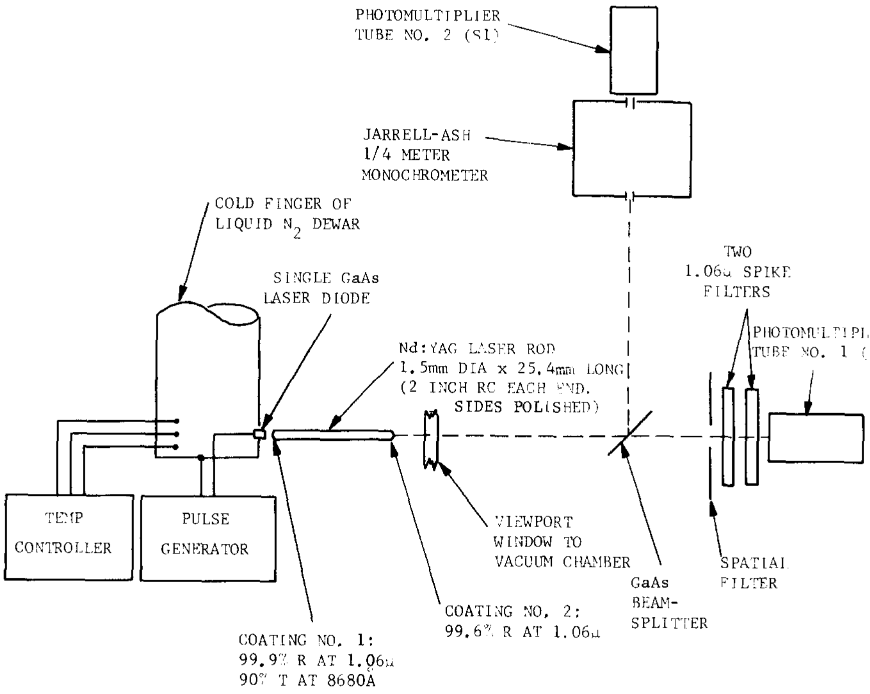

FIG. 1. Layout for GaAs diode-pumped Nd:YAG laser experiment.

is held by means of a Teflon collet, and can be positioned to within 0.010–0.020 in. of the emitting surface of the GaAs laser using a special support jig. When the assembly is completed, the emitting surface of the GaAs laser can easily be seen through the other end of the laser rod.

Using a GaAs beam splitter and a Jarrell-Ash $\frac{1}{4}$-m monochrometer, the output of the pulsed GaAs laser was continuously monitored to determine the effective absorption of pump light in the YAG laser rod as the temperature of the GaAs laser was tuned. As the peak current to the laser diode was increased, it became necessary to readjust the temperature controller setting to compensate for the wavelength shift associated with increased junction heating.

The GaAs diode laser was driven by a burst of 20 to 30, 500-nsec-wide pulses at 100 kHz. The burst was repeated about 16 times per second. Typical oscilloscope traces showing laser output and GaAs current pulses are shown in Figs. 2(a) and 2(b). In Fig. 2(a), the 1.06-μ fluorescence can be seen increasing in a step-function manner as each successive 500-nsec pulse of GaAs pump light is absorbed. As the lasing threshold is exceeded for the Nd:YAG crystal spikes abruptly appear in the 1.06-μ output. At a point just above threshold, these spikes had a measured intensity at least 50 times that of the fluorescence envelope.

In Fig. 2(b), the pump power delivered to the laser rod during the first 20 pulses of the burst was increased to about 1.9 times the threshold value, and the length of the burst was increased by 50%. Strong lasing spikes can be seen over the final 130 μsec of the burst, and a definite 1:1 correspondence exists between pump-light pulses and laser spikes.

In Figs. 2(a) and 2(b), the apparent negative swing in the current pulse was an artifact of the current measuring technique used during the experiment. (Subsequent comparison of that technique with results obtained using a calibrated current probe confirmed this.)

An Eppley thermopile was used to measure average GaAs output power at the proper temperature before the laser rod was inserted in place. The lasing threshold was found to be approximately 55–60 μJ per burst; in rough agreement with the first-order approximation to the threshold described in the Appendix. This energy was usually delivered in the form of 20, 3-μJ pulses about 10 μsec apart. Since the time required to deliver each burst was less than the fluorescence lifetime for the upper level of the lasing transition (200–230 μsec),[5-7] the Nd:YAG laser rod was able to effectively integrate the absorbed pump light over the burst, and build up an inversion sufficient to produce lasing. (It should be pointed out that no special effort was made to cool the laser rod in order to reduce the threshold power requirements.)

Measurements made on the monochromator indicated that GaAs pulses emitted toward the end of the burst had longer peak wavelengths than those emitted initially, due to junction heating. This effect, combined with the natural emission linewidth and the effects of chirp during a single pulse produced a spectral envelope of 25–50 Å FWHM, depending on the individual laser diode. Increasing the 500-nsec duration of the individual pulses much beyond 750 nsec was not effective in appreciably increasing laser output power, since the resulting broader spectral envelope had less overlap with the 8680-Å YAG absorption line.

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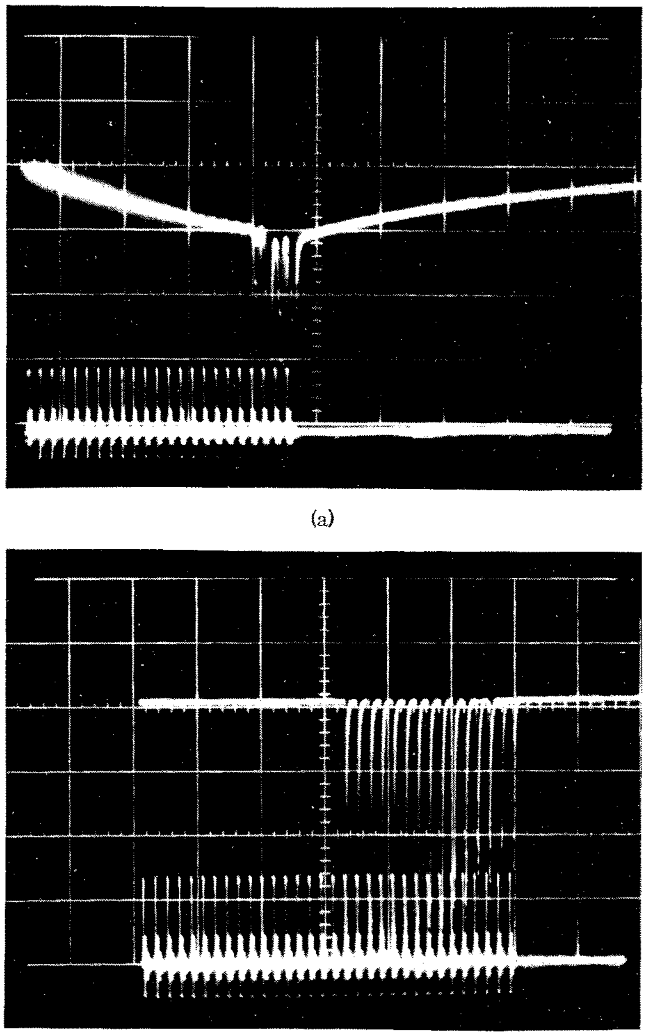

(a)

(b)

FIG. 2. (a) Laser output and GaAs current pulses just above threshold (20 A peak current). Upper trace: 1.06-μ output of laser (0.5 V/cm); lower trace: current probe (20 A/cm); sweep: 50 μsec/cm. (b) Laser output and GaAs current pulses well above threshold (28 A peak current). Upper trace: 1.06-μ output of laser (10 V/cm); lower trace: current probe (20 A/cm); sweep: 50 μsec/cm.

APPENDIX: THRESHOLD CALCULATION FOR GaAs DIODE

Pumped Nd : YAG laser experiment

The condition for oscillation at laser threshold is given by:[8]

$$R_1R_2\exp[2(g_t-\alpha)l-L_M]=1 \ .$$

Hence,

$$2(g_t-\alpha)l=L_M-\ln(R_1R_2) \ ,$$

$$g_t=\alpha+\frac{L_M-\ln(R_1R_2)}{2l} \ ,$$

where g= threshold gain coefficeient in cm^{-1}, α= absorption loss coefficient at $1.06\mu=0.002$ cm^{-1},[9] L_M = miscellaneous round-trip losses (including scattering and diffraction) = 0.01 (estimate), R_1 = reflectivity of output coupler = 0.996, R_2 = reflectivity of HR coating = 0.998, and l = rod length = 2.54 cm.

Inserting these values into the above expression yields

$$g_t=0.0052 \text{ cm}^{-1}$$

which is the gain required to reach threshold. By definition, this gain coefficient is equal to the small-signal gain coefficient g_0 given by[10]

$$g_0=\frac{\lambda^2\Delta N}{8\pi n^2\Delta\nu t_{sp}} \ ,$$

where λ = wavelength $=1.06\times10^{-4}$ cm, ΔN = inversion/cm^3, n = index of refraction = 1.82,[11] $\Delta\nu$ = Lorentzian half-width of the transition $=13.5\times10^{10}$ sec^{-1} [10] at 300 °K, and t_{sp} = spontaneous radiative lifetime $=230\times10^{-6}$ sec.[10]

Hence, the inversion required to produce a gain of $g_t=g_0=0.0052$ cm^{-1} is given by

$$\Delta N=\frac{8\pi n^2\Delta\nu t_{sp}g_0}{\lambda^2} \ ,$$

$$\Delta N=1.20\times10^{15} \text{ cm}^{-3} \ .$$

Neglecting those Nd^{3+} ions that relax to the lower lasing level during the 200-μsec burst, we can approximate the inversion created during a single burst of GaAs pump light by

$$\Delta N'=\frac{E\eta_1\eta_2\eta_3}{h\nu V} \ ,$$

where E = energy contained in a single GaAs burst, $h\nu$ = average energy of photons at 8680 Å $=2.28\times10^{-19}$ J, η_1 = coating transmission = 0.90, η_2 = effective spectral overlap of GaAs output with Nd:YAG absorption line = 0.50 (based on experimental observations), η_3 = quantum efficiency of 1.06-μ fluorescence = 0.63,[12] and V = rod volume = 0.045 cm^3.

Hence, if $\Delta N'=\Delta N=1.20\times10^{15}$ cm^{-3} then

$$E=\frac{Vh\nu\Delta N'}{\eta_1\eta_2\eta_3}$$

and

$$E=44 \ \mu\text{J} \ .$$

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