field patterns at different pumping currents. The lobe half-widths are about two to three times diffraction-limit value (i.e., $\approx 1°$ for an in-phase 76-μm-wide array with amplitudes weighted as indicated by the near-field pattern) at low pumping currents. This indicates a degree of phase-locked operation. The lobe half-width increases gradually to $\approx 8°$ at the 250-mW output level. However, these beam widths are still narrower than that of a single ridge waveguide laser with 4-μm rib width, which is about 19° assuming approximately sinusoidal field distribution. This indicates that some coherent coupling exists between adjacent lasers even at high pumping currents. All the laser arrays tested showed single-lobe patterns at high pumping currents. We often observed double-lobe patterns at pumping currents slightly higher than the threshold current. The transition from out-of-phase to in-phase operation clearly shows the effect of pumping currents in the coupling regions. Stable far-field intensity distribution is observed to maximum output power. This wide range of stability as a function of output power is believed to be from both the index-guided nature and the strong coupling between lasers inherent in this structure. The increase in beam width over the diffraction-limit value, indicates that more than one eigenmode is excited as pointed out by Butler *et al.*[3] This may be due to a variety of factors. Misalignment of lasers with crystal directions, variation of resonator lengths, and nonuniformity inherent in liquid phase epitaxy growth are among the factors that must be investigated.[9] The near-field intensity distribution is also consistent with a quasi-in-phase shift between individual diodes. Distinct light spots are only evident at a pumping current slightly higher than the threshold current. At higher pumping currents, the lasers appear to emit fairly uniformly. Although the lasers showed good lateral beam quality, they only operated in a single-longitudinal mode at a pumping current slightly higher than the threshold current.

In conclusion, we have described a phase-locked semiconductor laser array that emits a single far-field beam parallel to the plane of *p-n* junction. This high degree of collimation results from intentional pumping at coupling region among elements of arrays. Linear outputs greater than 250-mW pulsed power have been obtained without facet coatings. The results are highly reproducible if care is taken in Zn diffusion. The simplicity of this structure and fabrication process makes this approach attractive for many practical applications.

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High-speed photoconductivity and infrared to visible up-conversion in GaP light-emitting diodes

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In GaP:N (Zn,Te) light-emitting diodes extrinsic photoconductivity and infrared to visible up-conversion have been investigated by short laser pulses at 10-μm wavelength. A time constant of the order of 1 ns was observed indicating that free infrared excited hole to bound donor recombination yields the fast response.

Extrinsic photoconductivity and infrared induced electroluminescence have been observed in GaP light-emitting diodes (LED's), providing a simple method of infrared to visible up-conversion.[1] The mechanism is based on the photoionization of shallow impurities at low temperatures ($T < 40$ K) where almost all carriers are bound to impurities. Infrared radiation, whose quantum energy exceeds the binding energy of shallow impurities, induces a photocurrent through the diode and thus leads to visible luminescence. In the present letter we report on investigations of the transient behavior of GaP LED's due to infrared excitation by short laser pulses. The measurements revealed that the time constant of the photoconductivity and the up-conversion processes is of the order of 1 ns. Thus, at low temperatures GaP LED's represent fast IR detectors and may potentially be useful for high-speed IR imaging.

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Green emitting GaP:N (Zn,Te) diodes prepared by liquid phase epitaxy on Te-doped n-conducting substrates were employed. Alloyed metal electrodes covered the full size of the substrate and had the shape of a narrow cross on the p-face leaving space (about 10^{-3} cm^2) for IR radiation into the material. Samples were mounted in an optical cryostat and immersed in liquid helium at 4.2 K. A TEA CO_2 laser at 10.6-μm wavelength emitting a pulse train due to self-mode locking and a high pressure TE CO_2 laser have been used as exciting sources. Depending on the feedback conditions, the high pressure laser radiated either smooth pulses or modulated pulses with periods less than 1 ns.[2] Smooth pulses were passed through a plasma shutter yielding a sharp edge in the time dependence of the intensity. The visible light emitted by the diodes was collected by a quartz multifiber optical light guide and fed spectrally unresolved into a fast photomultiplier (Hamamatsu R928) outside the cryostat. Signals due to single laser pulses were recorded using a Biomation 6500 transient recorder with 2-ns sampling intervals or by a Tektronix R7912 transient digitizer of 0.5-ns resolution. Averaging over many pulses was not possible because of the jitter between electrical discharge and laser action.

Photoconductivity was observed on forward and reverse bias conditions whereas electroluminescence occurred in forward biased diodes only. The bias voltage in the forward direction was varied from 4 V, where photoconductivity first became clearly observable, up to the threshold of double injection instability[1] being about 200 V in the employed diodes. Up-conversion could be recorded for voltages higher than 20 V. Within these voltage ranges the transient structure of the signal was independent of the bias voltage.

Typical measurements are displayed in Figs. 1–3. In the Biomation recordings (Figs. 1,2) photoconductivity and electroluminescence are practically synchronous. The pulse

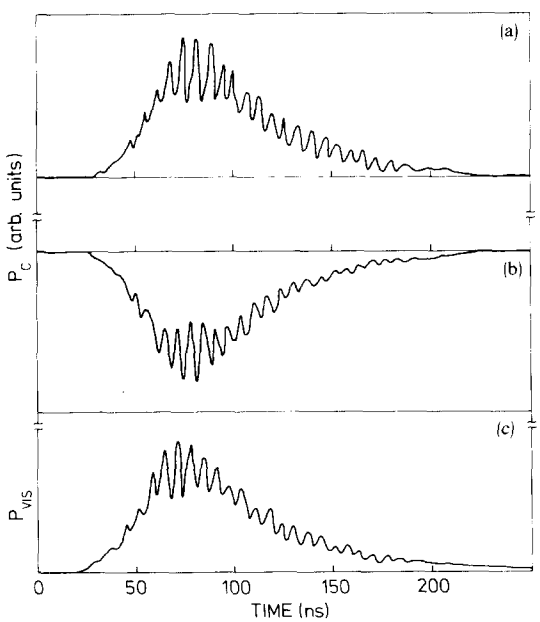

FIG. 1. Pulse shape of the TEA laser pulses detected by a GaP LED. Peak power is approximately 200 W, diode bias 40 V. (a) Photocurrent P_c for forward biased LED. (b) Photocurrent P_c for reverse bias. (c) Up-converted light P_{vis} as monitored for forward bias by a photomultiplier.

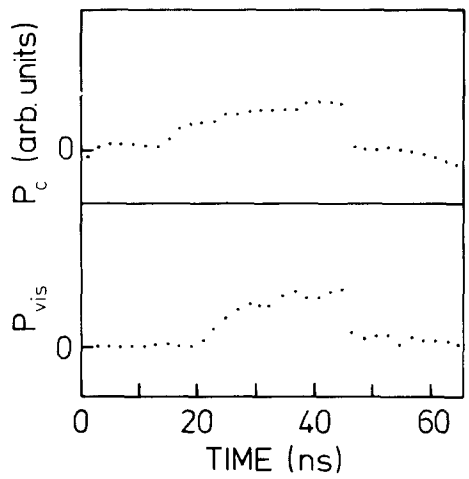

FIG. 2. Shape of a high pressure CO_2 laser pulse with sharp intensity cutoff produced by a plasma shutter. Peak power is approximately 200 W, diode bias 20 V. (a) Photocurrent P_c for forward biased LED. (b) Up-converted light P_{vis} monitored for forward bias by a photomultiplier.

train due to mode locking (Fig. 1) follows instantaneously the laser emission as could be proved by comparing the signal with that of a fast Ge photon-drag detector. In the measurements using the plasma shutter the signals decrease by almost their full magnitude within a sampling interval of 2 ns. Applying the modulated output of the high pressure CO_2 laser in photoconductivity even shorter structures could be resolved as shown in Fig. 3. From these measurements we deduced upper limits of the time constants of about 2 and 0.5 ns for the up-conversion and the photoconductivity, respectively. The measurement of the electroluminescence response time was limited by the bandwidth of the applied photomultiplier and the true luminescence decay time might be shorter, probably as short as that of the photoconductivity.

The photocurrent was found to be directly proportional to the laser power in the range of 10–200 W for the CO_2 laser corresponding to intensities ranging from 10 to 200 kW/cm^2 onto the LED. The current responsivity at 40-V bias voltage was about 2×10^{-4} A/W being somewhat smaller than for cw irradiation. The external quantum efficiency η_{LED}, i.e., the ratio of the number of up-converted visible photons to the number of photoelectrons, was about 10^{-3} for the laser

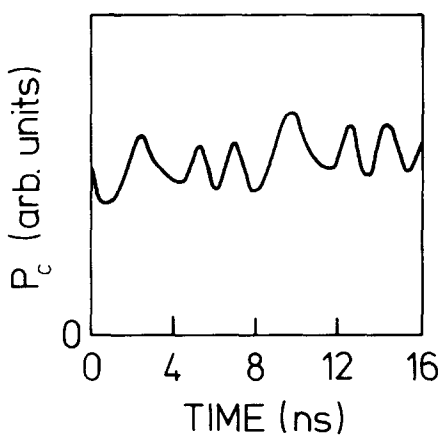

FIG. 3. Part of the pulse train of the modulated output of a high pressure CO_2 laser detected by a GaP LED in photoconductivity.

pulses used in these experiments, which is again lower than η_{LED} under cw conditions (then $\eta_{LED} = 3\times10^{-3}$) implying that a different recombination mechanism yields the fast response.

At liquid helium temperature radiative decay of excess minority carriers in GaP:N diodes occurs by donor acceptor (DA) pair recombination and by recombination of excitons bound to nitrogen and nitrogen complexes (NN lines).[3,4] Under cw excitation both recombination mechanisms could be identified in the present diodes. The DA recombination yielded a broad structureless band. This indicates that the recombination takes place in the space-charge region of the diode where the high electric field broadens the lines belonging to distinct pair distances because of the random orientation of DA pairs.[5] The majority of radiative transitions was found to be due to DA pair recombination rather than to the decay of bound excitons. The maximum transition rate[5] for Zn-Te pairs is 8.6×10^{6} s^{-1} which is, however, much too small to explain the fast response. The decay time of the NN lines is about 30 ns at liquid He temperature,[3] being again too long. Besides these low-temperature processes at liquid nitrogen temperature free hole to bound donor transitions were observed[5,6] which are in contrast to free electron to bound acceptor transitions favored by selection rules.[7] The radiative lifetime[5] of this process was estimated to be less than 2.5 ns, being very close to the upper limit of the response time measured in the present experiments for the fast luminescence component. Therefore, it seems reasonable to assume that free to bound transitions of this kind are responsible for the observed fast photoconductivity and infrared induced electroluminescence. The high power irradiation and the high electric field inside the sample produce a hot hole distribution whose effective temperature may be sufficiently high to allow for free to bound transitions. The time dependence of the electroluminescence and the photoconductivity within the lifetime of the free holes are both controlled by the transient hole concentration explaining the observed almost synchronism of electroluminescence and photoconductivity and also the linear dependence on laser power. Free holes decay either by the anticipated free to bound radiative transitions or by being captured by ionized acceptors. Capture cross sections of shallow impurities are very large[8] and recombination times in the range of 1 ns are typically observed in high compensated materials.[9] Thus, the total response time might be determined by this latter process being even shorter than the free hole to bound donor radiative lifetime.

In conclusion, we have demonstrated that GaP LED's of commercially available quality are very fast photoconductors and up-converters. Preliminary measurements of the IR spectrum showed that the diodes are applicable in a broad spectral range covering the near and middle infrared up to about 20-μm wavelength.[10] Experiments carried out with a pulsed dye laser at 0.7-μm wavelength yielded a similar behavior in the transient response as described above. Finally we note that the up-conversion scheme described here represents a new method particularly useful to investigate fast radiative decay in semiconductors, because the exciting IR radiation may easily be discriminated from the visible fluorescence even for arbitrarily short times after excitation.

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