

Carrier lifetime in HgTe/CdTe superlattices grown by photoassisted molecular beam epitaxy

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We report excess carrier lifetimes of several hundred nanoseconds in HgTe/CdTe superlattices grown by photoassisted molecular beam epitaxy. The structures were doped either *n*-type in the low 10^{15} cm^{-3} range or *p*-type in the low 10^{16} cm^{-3} range, and were designed for peak response in the long-wave infrared regime. The measured lifetimes, recorded by the transient photoconductivity technique, approach values calculated for alloys of equivalent band-gap energy. They indicate that recombination at the superlattice interfaces has been substantially reduced and underscore the recent progress achieved in superlattice growth technology.

More than a decade has passed since HgTe/CdTe superlattices were first proposed as an alternate structure for the fabrication of long-wave infrared detectors, replacing the more traditional HgCdTe alloy.¹ Despite the early recognition that this configuration offered some attractive potential advantages over the HgCdTe alloy of equivalent band-gap energy,² particularly for very long wave detection application, it was not until recently that actual photodiodes with a remarkable 66% peak quantum efficiency in the midwave range were finally reported.³ These devices, operating at a wavelength of about $4.9 \mu\text{m}$ at 78 K, constituted the first reported demonstration of superlattice detectors exhibiting a quantum efficiency exceeding a few percent. This development has revitalized efforts to extend this achievement toward longer wavelengths. A critical requirement for success is the ability to grow extremely high-quality interfaces between successive layers, in order to minimize excessive interface recombination which would otherwise offset the reduction in dark current expected from the superlattice configuration. A measure of the quality of these interfaces is provided by the excess carrier lifetime. Interestingly, in spite of the considerable amount of fundamental research invested in these novel structures over the last decade, we are aware of very few reports of carrier lifetimes published in the open literature.^{4,5} Lifetimes in the neighborhood of 10 ns were reported, either measured by photoconductive decay⁴ or calculated from observed dark currents in MIS structures.⁵ In this letter, we report excess carrier lifetimes in HgTe/CdTe superlattice structures of several hundred nanoseconds, which approaches members typically observed and calculated in good quality bulk material of comparable band-gap energy and doping levels.

The HgTe/CdTe superlattices were grown directly on (211) B-oriented CdTe substrates in a custom MBE machine modified for photoassisted molecular beam epitaxial

(PAMBE) growth, as described elsewhere.³ There is approximately a 10%–15% concentration of Hg atoms in the CdTe barrier layers due to a continuous Hg overpressure during growth.

Excess carrier lifetimes were measured both at GE and NRL by monitoring the dynamics of the photoconductive decay observed upon suddenly terminating an illuminating laser pulse.^{6–8} The illumination is provided by an AlGaAs multiquantum well injection laser obtained from Spectra Diode Labs (Model SDL-2100-E1). The beam characteristics of these lasers are ideally suited for focusing their far field, by means of a simple spherical lens, onto a narrow strip of the sample's surface between two ohmic contacts. The photoconductive sample is placed in series with a battery and either a passive 50- Ω load resistor or the input of a wide band, 20 dB amplifier (Hewlett-Packard, Model 461 A), with a bandwidth of 150 MHz. The changes in photoconductive current flowing through the circuit in response to changes in illumination are monitored by sensing the time-dependent voltage developed across the load. The signal is processed with a digital oscilloscope (Tektronix, Model 7854) to display the natural logarithm of the signal versus time. With an estimated radiant power density of 1 W/cm^2 incident on the sample's surface, nonlinear effects are often observed in the form of a faster-than-exponential initial decay,^{6,9} the magnitude of which depends strongly on the illumination level. The time constant is extracted from the linear portion of the curve, after the initial accelerated decay has died out. The time constant associated with turning off the laser is about 25 ns. Hence, our carrier lifetime measurements are reliable down to that limit.

Figure 1 displays experimental lifetime results obtained on a HgTe/CdTe superlattice (No. 617) which was not intentionally doped. Hall measurements indicated *n*-type conductivity, with a carrier concentration of about $3 \times 10^{15} \text{ cm}^{-3}$ at 77 K. Lifetimes near 400 ns were measured at temperatures below about 100 K. Figure 1 also shows calculated lifetimes in bulk HgCdTe of equivalent band-gap energy and similar doping levels for a number of

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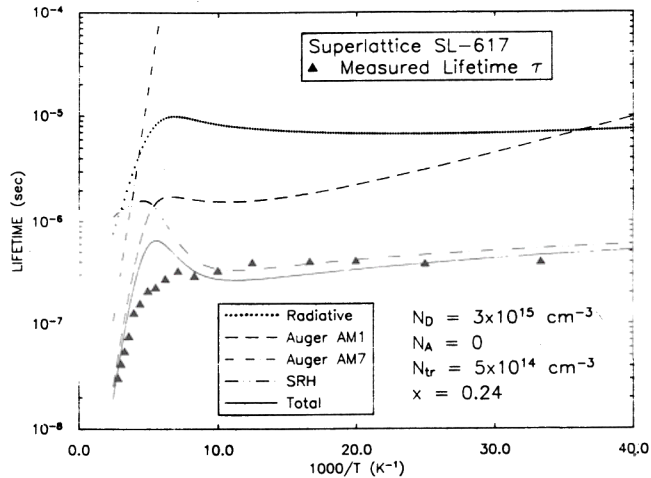


FIG. 1. Carrier lifetime vs reciprocal temperature for superlattice SL-617. The calculated curves of the equivalent x -value alloy identify the contributions of various recombination processes.

recombination processes, including radiative, Auger AM1, Auger AM7, and Shockley-Read-Hall (SRH).¹⁰ The method of calculation is identical to that outlined in Ref. 6. The SRH trap energy level was assumed to be midgap. The observed lifetimes are about one order of magnitude shorter than those calculated based on the Auger AM1 process alone. The measured data can be brought in approximate agreement with calculations by assuming a SRH trap density of $5 \times 10^{14} \text{ cm}^{-3}$. Note that our simplified calculations treat the SRH centers as recombination sites homogeneously distributed through the bulk. In a superlattice, localized interface states play a similar role. Indeed, we believe that excessive interface recombination is the primary mechanism which has kept carrier lifetimes in superlattices short up until now. A more refined theory of carrier lifetime, including the effect of interface states, needs to be developed to establish the ultimate potential of superlattices. Such a theory might provide better agreement with the experimental data in the temperature range where the sample becomes intrinsic.

An infrared photoluminescence¹¹ spectrum obtained at liquid nitrogen temperature on the same piece of material is shown in Fig. 2. The data feature a strong and sharp peak centered at an energy of 165 meV, with a full width at half maximum (FWHM) of about 16 meV. Photodiodes made from this superlattice material would have a cutoff wavelength near $7.5 \mu\text{m}$. The Cd mole fraction of the equivalent homogeneous bulk alloy is 0.24. The sharpness and brightness of the photoluminescence peak is a further confirmation of the quality of the superlattice. As a point of reference, the best bulk HgCdTe, grown by the traveling heater method, measured at 77 K in our system typically has a FWHM ranging from 25 to 30 meV and a radiative efficiency about half that measured in this superlattice, while indium antimonide grown by liquid phase epitaxy has a FWHM of 9 meV and is 2-3 times more intense. The spectrum shown in Fig. 2 also compares favorably with other published photoluminescence data on superlattices.^{12,13}

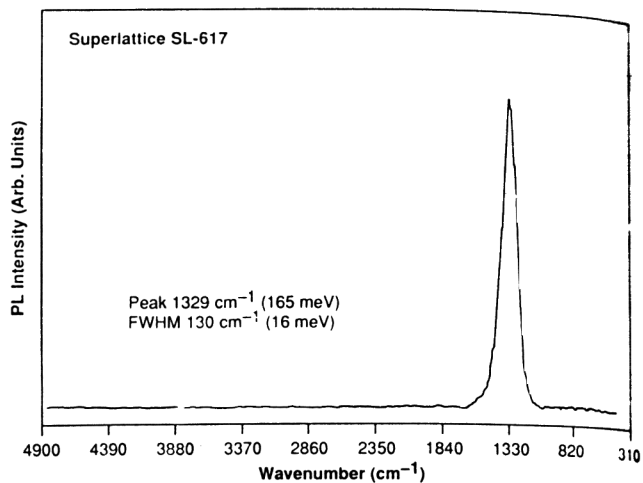


FIG. 2. Photoluminescence spectrum of superlattice SL-617 at liquid nitrogen temperature.

Figure 3 shows results from another superlattice (No. 632) which, unlike the previous one, was intentionally doped p -type by incorporating arsenic into the CdTe layers of the superlattice. IR photoluminescence of this material peaked near 135 meV at 77 K (expected cutoff wavelength $9.2 \mu\text{m}$) with a full width at half maximum of about 35 meV. This latter parameter is larger than in superlattice No. 617 because the PL spectrum is actually composed of two subpeaks separated by approximately 10 meV. The lower energy subpeak has been attributed to a transition associated with the arsenic dopant.¹⁴ The fact that the double nature of this peak can be observed at all, even at a temperature as high as 77 K, is indicative of the quality of the material. As was the case in Fig. 1, Fig. 3 also shows the calculated lifetime in an equivalent alloy with a cadmium mole fraction of 0.23 to match the observed photoluminescence peak. It was assumed in the calculation that this sample contained the same background of residual donors as did the unintentionally doped sample No. 617, as

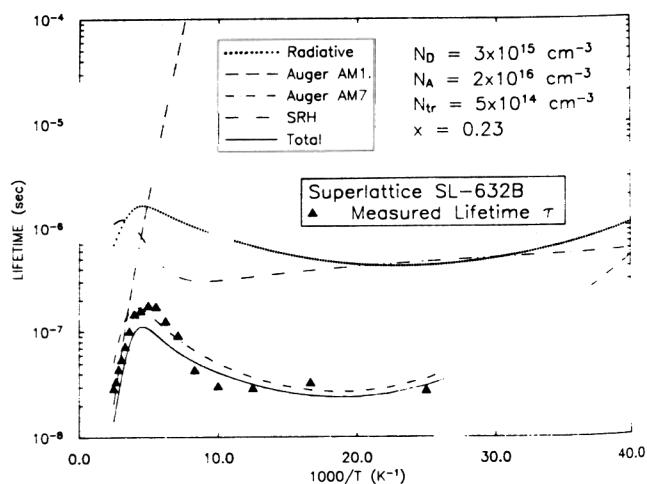


FIG. 3. Carrier lifetime vs reciprocal temperature for superlattice SL-632B. The calculated curves of the equivalent x -value alloy identify the contributions of various recombination processes.

well as the same concentration of traps. The calculated temperature dependence of the lifetime agrees surprisingly well with the experimental data, assuming an acceptor concentration of $2 \times 10^{16} \text{ cm}^{-3}$. This number matches the arsenic concentration, as measured by SIMS.¹⁴ Based on the calculation, the lifetime in this *p*-type sample is limited by the AM7 process over the entire temperature range investigated.

The excess carrier lifetimes reported in this letter indicate that progress is being made in HgTe/CdTe superlattice growth technology. PAMBE is emerging as a very promising epitaxial growth technique capable of producing superlattice structures whose quality approaches that of bulk material. The structural perfection of the material is improving to the point where interface recombination is now becoming a manageable problem. The achievement of long lifetimes in LWIR superlattices is a critical step towards the realization of superlattice-based IR detectors. With further advances sure to be realized, one can envision with increasing confidence that the theorized performance advantages of superlattice-based very long wave infrared photodiodes are on the verge of finally becoming reality.

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- ¹J. N. Schulman and T. C. McGill, *Appl. Phys. Lett.* **34**, 663 (1979).
- ²D. L. Smith, T. C. McGill, and J. N. Schulman, *Appl. Phys. Lett.* **43**, 180 (1983).
- ³K. A. Harris, T. H. Myers, R. W. Yanka, L. M. Mohnkern, and N. Otsuka, *J. Vac. Sci. Technol. B* **9**, 1752 (1991).
- ⁴C. A. Hoffman, J. R. Meyer, E. R. Youngdale, J. R. Lindle, F. J. Bartoli, K. A. Harris, J. W. Cook, Jr., and J. F. Schetzina, *Phys. Rev. B* **37**, 6933 (1988). See also: C. A. Hoffman, J. R. Meyer, E. R. Youngdale, J. R. Lindle, F. J. Bartoli, J. W. Han, K. A. Harris, J. W. Cook, Jr., and J. F. Schetzina, *J. Vac. Sci. Technol. A* **6**, 2785 (1988).
- ⁵M. W. Goodwin, M. A. Kinch, and R. J. Koestner, *J. Vac. Sci. Technol. A* **6**, 2685 (1988).
- ⁶J. Bajaj, S. H. Shin, J. G. Pasko, and M. Khoshnevisan, *J. Vac. Sci. Technol. A* **1**, 1749 (1983).
- ⁷R. Fastow and Y. Nemirowsky, *J. Appl. Phys.* **66**, 1705 (1989).
- ⁸R. Zucca, D. D. Edwall, J. S. Chen, and S. L. Johnston, *J. Vac. Sci. Technol. B* **9**, 1823 (1991).
- ⁹John P. McKelvey, *Solid State and Semiconductor Physics* (Harper and Row, New York, 1966), Sec. 10.
- ¹⁰P. E. Petersen, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic, New York, 1981), Vol. 18, p. 121.
- ¹¹A. R. Reisinger, R. N. Roberts, S. R. Chinn, and T. H. Myers, *Rev. Sci. Instrum.* **60**, 82 (1989).
- ¹²K. A. Harris, S. Hwang, D. K. Blanks, J. W. Cook, Jr., J. F. Schetzina, N. Otsuka, J. P. Baukus, and A. T. Hunter, *Appl. Phys. Lett.* **48**, 396 (1986).
- ¹³J. P. Baukus, A. T. Hunter, J. N. Schulman, and J. P. Faurie, *J. Appl. Phys.* **64**, 283 (1988).
- ¹⁴K. A. Harris, R. W. Yanka, L. M. Mohnkern, A. R. Reisinger, T. H. Myers, Z. Yang, Z. Yu, S. Hwang, and J. F. Schetzina, *J. Vac. Sci. Technol.* (to be published).