Infrared absorption measurement and analysis of HgTe–CdTe superlattices

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The near-band-gap optical properties of superlattice are essential in determining the usefulness of these structures for application in infrared systems. In this paper we report on studies of a HgTe–CdTe superlattice. The optical characterization of the superlattice in the infrared was carried out by measuring its photoluminescence, transmission, and photoconductivity spectra. Results of these measurements as functions of temperature are presented, as are the theoretically calculated absorption spectra. We obtained good agreement between different measurement techniques and the theoretical model for the optical absorption and band gap.

I. INTRODUCTION

HgTe–CdTe superlattices have been proposed as useful infrared detectors for infrared systems.[1,2] These structures consist of alternating thin layers of HgTe and CdTe grown on a suitable substrate. It is predicted that such a superlattice would have markedly different properties from a HgCdTe alloy of the same relative Hg and Cd compositions. Further the material properties, such as band gap and leakage current, would be dramatically less sensitive to variations in the growth process and thus should lead to better device yield and performance.

Since the structures are potentially useful as infrared detectors, their infrared properties are obviously of interest. While individual studies of infrared absorption[3] and photoluminescence[4] have been reported, the first multitechnique study is presented in this paper. We have performed optical measurements on a number of HgTe–CdTe superlattices. The measurements include infrared photoluminescence, photoconductivity, and infrared transmission and reflection studies. Results for all these techniques performed on one of the samples are presented and compared. We have also done theoretical calculations of the optical absorption of superlattices and compared these results to the measured values.

II. SAMPLE PREPARATION

The sample whose data are presented here was grown at the University of Illinois, Chicago Circle on a Riber 2300 molecular beam epitaxy machine that was specially tailored to handle Hg. The sample was grown to have 250 repeats of 38–40 Å of HgTe followed by 18–20 Å of CdTe on a (111) oriented $Cd_{0.96}Zn_{0.04}Te$ substrate.

The overall superlattice thickness was accurately measured by various techniques and the number of repeats was known. The individual layer thicknesses, however, were based on the calibration curves of the various sources in the molecular beam epitaxy machine. Thus these numbers were less confidently known.

III. EXPERIMENTAL

The infrared spectra were measured using a specially designed BOMEM model DA3.01 Fourier transform interferometric spectrophotometer with a KCl beam splitter. Samples were mounted in Janis Supertran Dewars which provided for temperatures from liquid He to room ambient.

The excitation source for the photoluminescence measurements was a Spectra Diode Laboratories model SDL 2410-C laser with an output wavelength near 8000 Å at room temperature. The photoluminescence from the sample was reimaged at the emission port of the BOMEM using KCl optics, and a Zn-doped Ge detector was used. A special measurement technique was developed to alleviate the effects of the ambient background.[5]

The infrared transmission measurements were made in the BOMEM with the same beamsplitter and detector. In this case the internal globar was used as the source. The Dewar was mounted at the normal sample position. Reference spectra of the empty Dewar were run at all sample measurement temperatures to compensate for thermal expansion of the cold surfaces in the Dewar. This causes the sample aperture to move relative to the infrared beam as a function of temperature and, as a result, give incorrect transmission values. Absorption spectra were calculated by taking the negative of the natural logarithm of the transmission curve, subtracting a constant amount due to reflectivity, and then dividing by the superlattice thickness. We did not correct for Fabry–Perot resonances which should occur due to the layered character of the overall structure.

The photoconductivity measurements were made with the sample in the same Dewar in the sample position of the spectrophotometer. The bias supply and transimpedance amplifier normally used with the Ge:Zn detector were used to provide bias and to measure the photoresponse of the sample, respectively. The superlattice was contacted by silver painting two contacts to the superlattice face. Small wires were held to the contacts by insulated clips. The photocon-
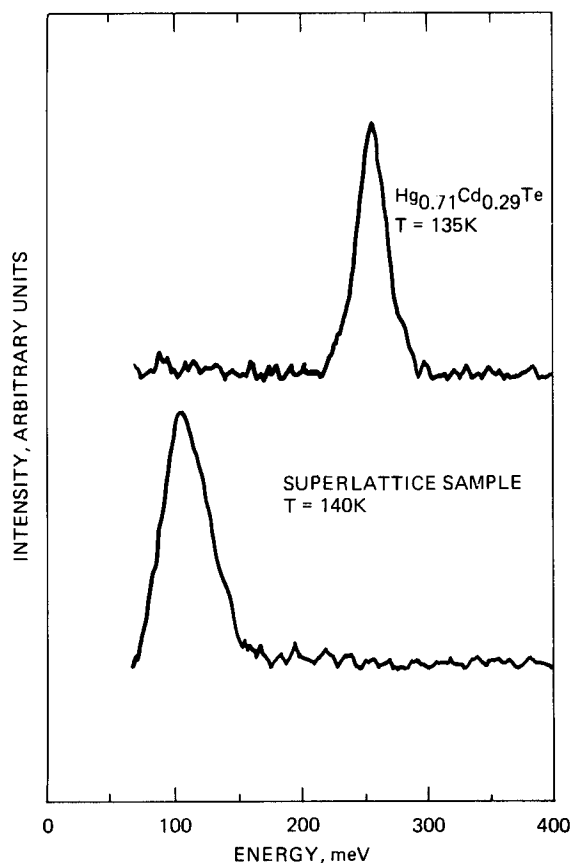
FIG. 1. Infrared photoluminescence spectra of a $Hg_{0.71}Cd_{0.29}Te$ alloy sample and the superlattice sample. The alloy spectrum was taken at 135 K, and the spectrum from the superlattice was taken at 140 K. The long wavelength cutoff of the optical response of the system is near 73 meV (17 μm). Each spectrum is plotted on a different vertical scale.

ductivity spectrum was obtained by dividing the response of the superlattice by that of the Ge:Zn detector. This corrected for the spectral responses of the source, beamsplitter, and instrument and Dewar optics, but not for that of the Ge:Zn detector. The detector response decreases gradually with increasing photon energy over this spectral range.

IV. THEORETICAL

The theoretical calculations use the second-order $k \cdot p$ method with spin-orbit splitting included. Two conduction and six valence band states are used as basis functions of the Hamiltonian for the bulk materials. The eight basis functions include: two states with Γ_6 symmetry, four states with Γ_8 symmetry, and two states with Γ_7 symmetry (the states split off by the spin-orbit interaction from the Γ_8 states). In CdTe, the Γ_6 states are higher in energy than the Γ_8 ones and therefore are conduction band states. In HgTe, the symmetry being inverted, the Γ_6 states are lower and, therefore, the Γ_8 states consist of both conduction and valence band states. The companion matrix of the bulk Hamiltonian for a given energy and wave vector parallel to the interface is diagonalized and complex band structure is obtained. The superlattice wave functions are expressed as a linear combination of the eigenvectors for the bulk materials. By requiring the superlattice wave functions to satisfy boundary conditions,

i.e., the continuity of the function and its derivative at the interface, and the Bloch condition, the superlattice band structure is obtained.[6,7]

The Luttinger parameters were taken from Ref. 7. We use 40 meV as the value of valence band offset.[8] The temperature dependence of the superlattice band structure is taken into account by assuming that it is determined by the dependence of bulk band structure on the temperature.[9] The HgTe and CdTe layers are assumed to be 12 layers thick (44.8 Å) and 4 layers thick (15 Å), respectively. The band gap of the superlattice is found to be 0.06 eV at 4.2 K and 0.16 eV at 300 K.

The value of the absorption was calculated for the electric field polarized parallel to the layers. The values of the imaginary part of the dielectric constant as a function of frequency, $\epsilon_2(\omega)$, were obtained for photon energies up to 0.4 eV by including the two lowest energy conduction subbands and the nine highest energy valence subbands. The absorption, $\alpha(\omega) = \omega \cdot \epsilon_2(\omega)/c \cdot n(\omega)$, was obtained by assuming that the index, $n(\omega)$, was a constant, 3.46, independent of frequency. This value is approximately that found in the bulk HgCdTe alloys.[10]

V. RESULTS

The optical characterization of the superlattice in the infrared was carried out by measuring its photoluminescence, transmission, and photoconductivity spectra. Results of these measurements as functions of temperature are presented, as are the theoretically calculated absorption spectra.

The photoluminescence spectrum of the sample at 140 K is shown in Fig. 1. Also shown in the figure is a photoluminescence spectrum for a HgCdTe alloy sample which has approximately the same Hg-to-Cd ratio as that of the superlattice, based on its growth parameters. All samples show a single broad peak in their response which is well above the noise level.

The superlattice shows a photoluminescence peak near 105 meV (11.8 μm) with a full width at half-maximum intensity of 42 meV. In contrast, the alloy exhibits a peak at about 260 meV (4.8 μm). The peak in the photoluminescence spectrum of the alloy is near its band gap. The photoluminescence peak from the superlattice occurs at a lower energy than the peak in the alloy sample, and is consistent with the predictions for superlattices.

The temperature dependence of the photoluminescence peaks for the superlattice sample is shown in Fig. 2. The circle of each point corresponds to the peak energy of its photoluminescence and the "error bars" correspond to the higher and lower half-intensity energies, not experimental error. The "flattening" of the lower energy points for the sample at the lower temperatures is due to the long-wavelength cutoff of the KCl optics used in the experiment. The curves are theoretical fits to the data which are discussed below.

We present the absorption spectra of the superlattice in the region of the band gap in Fig. 3. Data taken at both room temperature and liquid helium are shown. The spectra recorded at intermediate temperatures fell systematically between these curves and are not included for clarity. In Fig. 4, we present our theoretical results for the infrared absorp-
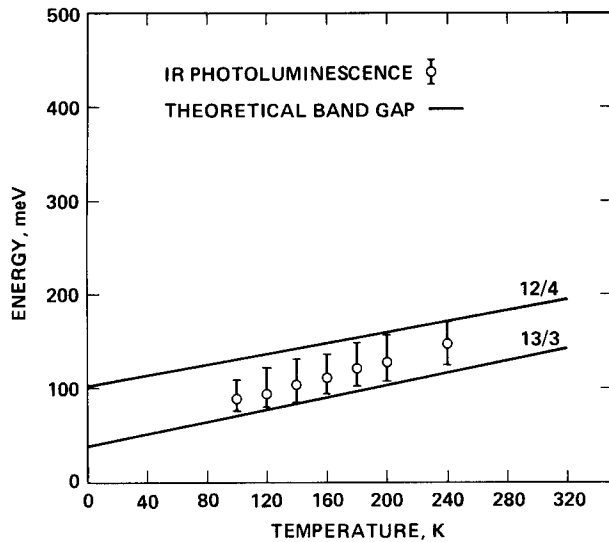
FIG. 2. Temperature dependence of the infrared photoluminescence signal from the superlattice. The circles represent the energy of the peak signal, while the bars indicate the energies of the half-intensity points. The lines are calculated curves for superlattices with the indicated number of HgTe layers/CdTe layers.

FIG. 4. Theoretical infrared absorption spectra of the superlattice.

tion of the superlattice.

Transmission spectra from two superlattices were taken at two different laboratories and in each case the data for a given superlattice were in good agreement. A test was run in one case in which a small platinum resistance thermometer was mounted on top of a superlattice sample to verify the Dewar temperature control accuracy and to check for photo heating effects. Good agreement was obtained between the control sensor and the platinum resistance thermometer indicating that the sample was indeed at the control temperature in both laboratories.

The photoconductive response spectrum of the superlattice at liquid helium temperature is shown in Fig. 5. As indicated above the system response was not completely removed from this data, however, the photoconductive edge is well defined since the remaining correction varies slowly with photon energy.

VI. DISCUSSION

In this section we will discuss the relative advantages and problems of each experimental technique as well as suggested improvements for them. Also the agreement between ex-
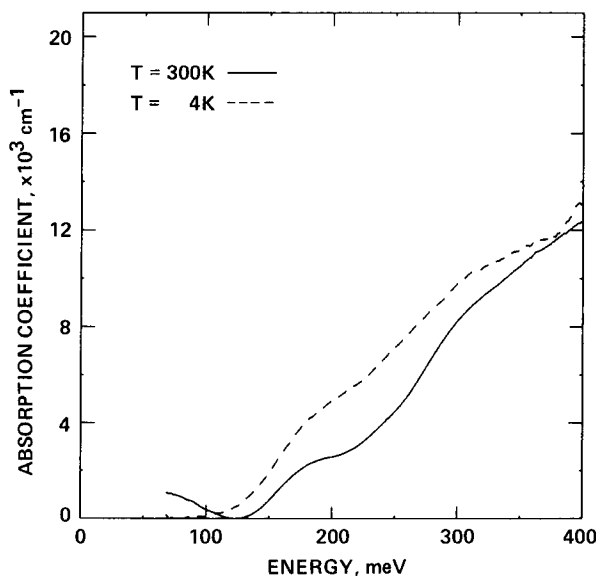

FIG. 3. Experimental infrared absorption spectra of the superlattice. The solid line was taken at 300 K and the dashed curve was obtained at liquid helium temperature. The spectra for intermediate temperatures fell between these two curves.
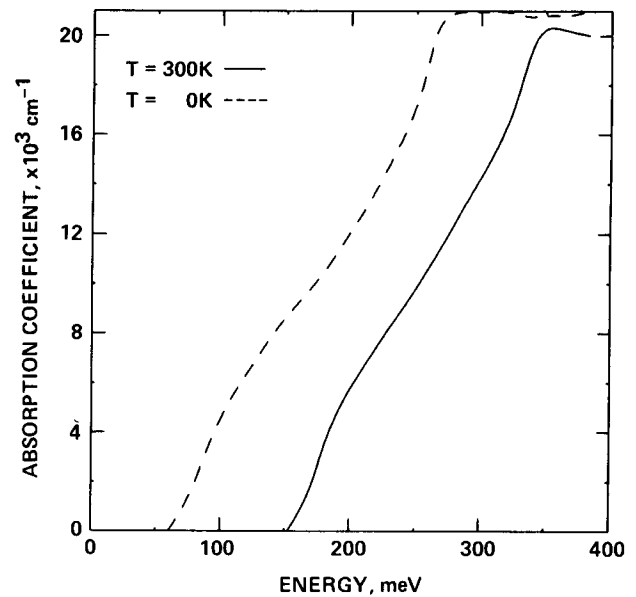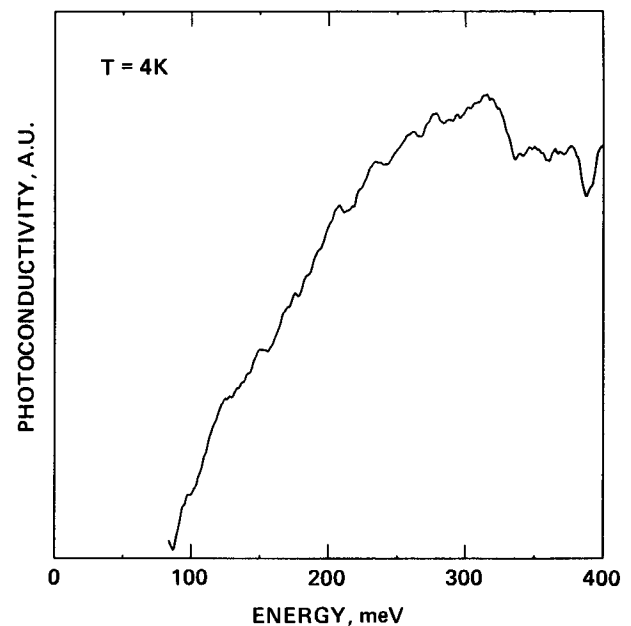

FIG. 5. Photoconductivity spectrum of the superlattice at liquid helium temperature. This curve is referenced to a Zn-doped Ge detector which has a gentle variation with wavelength in this spectral region.

periment and theory will be explored.

The photoluminescence data are quite clear cut and line positions and widths can readily be determined. However, the origin of the lines is not well understood. The spectral peaks appear to be due to recombination of electrons and holes near the respective band edges. The agreement with theory and photoluminescence results on HgCdTe alloy samples[11,12] tend to support this hypothesis.

If this is the case, we can compare the photoluminescence line positions with theory.[13] If we take into account the fact that the layer thicknesses should be discrete multiples of the compound layer spacing[13] and assume that the total layer thickness is fixed, we find that the photoluminescence peaks from the superlattice are best fit by 12 layers of HgTe (44.8 Å) and 4 layers of CdTe (15 Å). The theoretical curves for this set of parameters and for the 13/3 layer set are plotted in Fig. 2. Both sets of parameters appear to give a reasonable fit to the data. The 12/4 set of layers was tentatively chosen as a better fit than the 13/3 set primarily because these layer thicknesses correspond more closely to the growth conditions.

The status of infrared absorption measurement and interpretation is exactly opposite to that for photoluminescence. The interpretation of the absorption spectra is now well understood, as described above. However, there are a number of problems encountered in obtaining and analyzing the data. The samples consist of three distinct layers, and reflection occurs at each of these layers as well as at both faces. These wavelength dependent reflections cause periodic variations in the transmission and reflection spectra of the samples. Since the superlattice layers are quite thin, the overall absorbance of the samples is relatively small and thus these channeling or Fabry–Perot effects are predominant. The correction for these effects involves nonlinear curve fitting to transcendental equations and sorting through multiple roots.

As a result, it is not certain whether the variations in the curves of Fig. 3 are due to Fabry–Perot effects or to the details of the band structure as seen in the theoretical curves of Fig. 4. However, the temperature dependence of the experimental absorption data is much weaker than either the theory or the photoluminescence data.

A comparison of the measured absorption in Fig. 3 with the theoretical values in Fig. 4 suggests that the theoretical absorption shows more temperature dependence than that found experimentally.[14] Further the theoretical values of the absorption are almost a factor of 2 larger than the observed values. This difference, while significant, could result from a number of factors including: the reduction of the experimental data and the simplifications in the theory which does not include interdiffusion or exciton effects.

In spite of the experimental and data interpretation prob-

lems, it is clear that the agreement between experiment and theory is good. Theory and all the experimental techniques point to approximately the same band-gap energy for the sample.

VII. CONCLUSIONS

In summary, we have measured infrared photoluminescence, transmission, and photoconductivity of HgTe–CdTe superlattice samples and carried out theoretical studies of the near-band-edge absorption properties of these structures. We have observed the shift in band gap to lower energies compared to HgCdTe aloys with the same Hg-to-Cd ratio. This confirms that these structures do behave as has been predicted.

We have reported the first photoconductivity studies of a HgTe–CdTe superlattice and the first multiple technique optical study of these structures. We obtained good agreement between different measurement techniques and the theoretical model for the optical absorption and band gap.

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