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Shubnikov–de Haas oscillations in HgTe/CdTe superlattices grown by laser molecular-beam epitaxy

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Low-temperature Shubnikov–de Haas (SdH) oscillations and the Hall effect have been studied on a HgTe/CdTe superlattice grown by laser molecular-beam epitaxy. The results indicate that three subbands in the quantum well contribute to the conductivity. A line-shape fit of the SdH data also indicates that the intermediate SdH component has an electron effective-mass ratio which is five times larger than the mass ratio of the lower-frequency SdH component.
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INTRODUCTION

The inverted band structure of semimetallic HgTe makes the HgTe/CdTe superlattice (SL) a type-III system and a promising candidate for infrared detectors.[1] This SL system is superior to the bulk $Hg_{1-x}Cd_xTe$ alloy for infrared applications partly because box quantization of the quantum wells makes the band gap of the SL increase with decreasing HgTe layer thickness, without depending upon alloying effects as in the bulk alloy. High-quality HgTe/CdTe SL samples[2] which show the integer quantum Hall effect and large Shubnikov–de Haas (SdH) oscillations have already revealed new semiconductor physics such as antilocalization even though there have been only a few comprehensive transport studies of this unique type-III system. Previous investigators[2] have suggested multisubband conduction to explain the complicated SdH pattern observed in this system, but they were unable to characterize these carriers due to weak SdH oscillations. Our aim is to provide further insight into the band structure of the HgTe/CdTe system and also determine the relations between subband occupancy and SdH frequency in this multisubband system. Thus, we compare Hall effect measurements with SdH oscillations observed using field modulation techniques. The SdH oscillations have been fitted with the best recursive fit technique[3] in order to separate the oscillatory contributions of different subbands and determine the effective masses and scattering temperatures associated with these subbands.

EXPERIMENT

The HgTe/CdTe SL used in this study was grown by laser molecular-beam epitaxy (MBE).[4] The low growth temperature used in this technique is believed to produce less interdiffusion between the HgTe and the CdTe layers. Thus, these samples are superior to conventional MBE material. The sample consists of 12 periods of 90-Å HgTe and 40-Å CdTe on a (100) CdTe substrate. The magnetotransport measurements were made in the Van der Pauw configuration in magnetic fields, B, up to 70 kOe at temperatures, T, below 20 K. The SdH oscillations were enhanced using standard field modulation techniques. In order to simplify the fit to the SdH data, we have assumed that the oscillations obey the following semiempirical formula which is valid even for this narrow-gap system in the high-temperature, low-field limit

$$\rho=\rho_0+\sum_i A_i \exp[-\lambda(T+T_D^i)m_i^*/mB] \times\sin(2\pi F_i/B+\delta_i)\,. \qquad (1)$$

Here, m_i^*/m is the electron effective-mass ratio, T_D^i is the Dingle temperature, F_i is the SdH frequency, δ_i is the infinite-field SdH phase of the ith SdH component, and $\lambda=146.9$ kOe/K. We point out that the Dingle temperature[5] measures the broadening, Γ, of the individual Landau levels, $\Gamma=\pi k_B T_D$, and is related to the single-particle lifetime, τ_s, through $\tau_s=\hbar/(2\pi k_B T_D)$.

DATA AND DISCUSSION

In Fig. 1, we have shown a trace of the SdH oscillations observed in this HgTe/CdTe SL at $T=1.55$ K. The data imply more than two SdH components since the figure does not show a simple beating pattern in $1/B$. In order to extract the SdH frequencies, we have plotted in Fig. 2 the $d\rho_{xx}/dB$ extrema positions in $1/B$ versus integers; the half-cycle plot shows three linear regions with increasing $1/B$ which correspond to SdH frequencies $F_1=238$ kOe, $F_2=65$ kOe, and $F_3=12$ kOe, respectively. These frequencies are temperature independent to within experimental accuracy for $T<20$ K.

In Fig. 3, we have shown the line-shape fit to the SdH data over the field range 3–20 kOe [Fig. 3(a)], 8–20 kOe [Fig. 3(b)], and 25–60 kOe [Fig. 3(c)] for $T=1.55$ K. The temperature dependence of the exponential terms in Eq. (1) were used to measure the effective masses and the Dingle temperatures (see Table I). We were unable to

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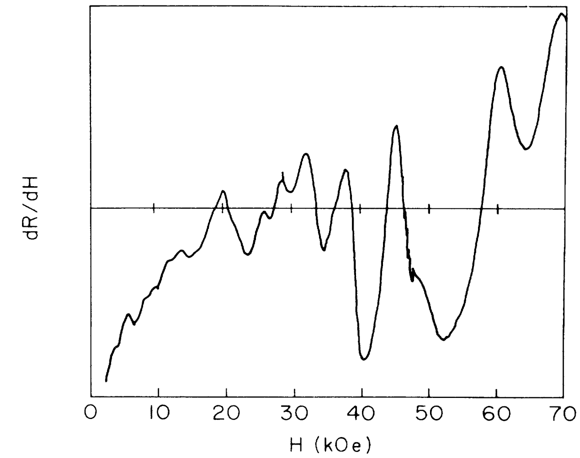

FIG. 1. Shubnikov–de Haas oscillations $d\rho_{xx}/dB$ vs the magnetic field H at 1.55 K for a HgTe/CdTe SL.

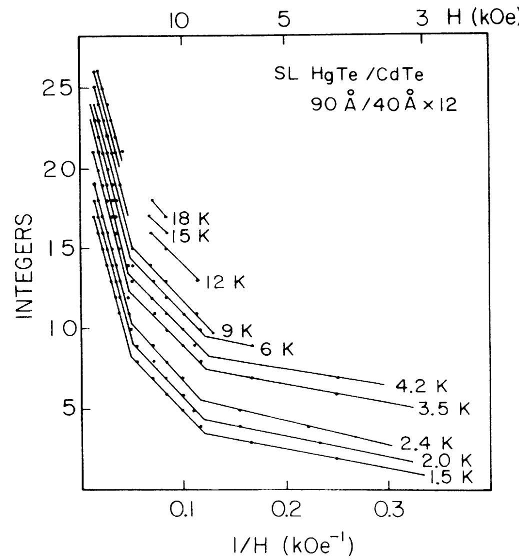

FIG. 2. Plot of the $d\rho_{xx}/dB$ extrema positions in $1/B$ vs integers for temperatures up to 18 K.

determine the mass for the $i=1$ SdH component partly because oscillations associated with this component occurred in the high-field, quantum Hall regime. We point out that the $i=2$ SdH component ($F=66$ kOe) has an effective-mass ratio which is a factor of 5 times larger than m^*/m for the $i=3$ SdH component ($F=12$ kOe). These results are consistent with our observation that SdH peaks associated with the $F=66$ kOe component are damped more strongly with temperature than the peaks due to the other two components. We estimate possible 20% error in our mass estimates due to approximating the SdH oscillations by simple damped sinusoids and also due to random errors. The Dingle temperatures indicate that sharp Landau levels are associated with these SdH components, i.e., $\hbar\omega \gg k_B T_D$.

Low-field Hall effect measurements indicated a linear-in-magnetic-field Hall voltage which is independent of temperature for $T<20$ K. The Hall mobility, μ, increased from 48 000 cm^2/Vs at $T=77$ K to 50 000 cm^2/Vs at $T=4.2$ K.

The SdH frequencies do not measure the individual subband populations in systems with many occupied subbands when the Fermi energy oscillates with the magnetic field and the degeneracy is independent of subband index.[6,7] As originally pointed out by Vinter and Overhauser,[6] the highest SdH frequency measures the total density rather than the population of the lowest subband at high-magnetic fields when $\hbar\omega^i \gg k_B T_D^i$. Thus, we have determined the subband populations given in Table I as follows: First, the highest SdH frequency measures the total density, i.e., $N_s = 2eF_1/\hbar = 1.1\times10^{12}$ cm^{-2}; a com-

TABLE I. Parameters determined for the three subbands of the HgTe/CdTe quantum well.

i	F (kOe)	m^*/m	T_D (K)	N_s (cm^{-2})	$E_F - E_i$ (meV)
1	237			8×10^{11}	
2	66.4	0.05	0.7	3×10^{11}	15
3	13.5	0.01	5.5	6×10^{10}	18

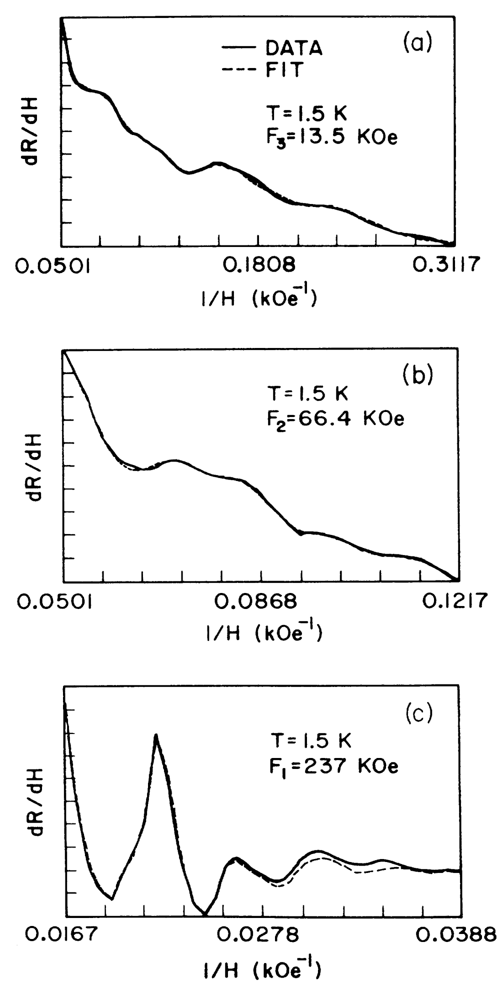

FIG. 3. Line-shape fit to the Shubnikov–de Haas data over the field range (a) 3–20 kOe, (b) 8–20 kOe, and (c) 25–60 kOe.

parison with the Hall effect suggests two active layers in the superlattice. Second, we assume the lowest SdH frequency measures the occupation of the $i=3$ subband, $N_3(B)=N_3(0)=2eF_3/\hbar$, since the large effective-mass ratio of the $i=2$ subband produces a quasistatic Fermi level over the range of fields ($B<10$ kOe) where oscillations associated with the $i=3$ subband are observed. Third, the average population of the $i=1$ and $i=2$ subbands differs from their zero-field value over the range of fields where oscillations associated with these subbands are observed when $i=3$ subband becomes completely depleted of its carriers. Thus, $N_2(B)=N_2(0)+\delta N_3$ and

$$N_1(B)=N_1(0)+(1-\delta)N_3=N_s-N_3(0)-N_2(B)\ .$$

Here, $\delta \sim N_2(B)/N_1 \sim F_2/F_1$ measures the fraction of carriers transferred from the $i=3$ subband to the $i=2$ subband in the extreme quantum limit for the $i=3$ subband.

Using these assumptions, we have found that the population of the $i=1$ subband is roughly 30% smaller than the value which would be obtained by assuming the highest frequency measures the $i=1$ subband density rather than the total density. The subband positions with respect to the Fermi energy, given in Table I, were calculated from the measured density and m^*/m neglecting nonparabolicity. We point out that the second and third subbands are equidistant from E_F although their mass ratios differ by a factor of 5; this feature is difficult to understand in the context of conventional band-structure models.[8] Nonparabolicity effects will just shift the subband minima away from the Fermi level without affecting our conclusions.

In summary, our study of the SdH effect in the HgTe/CdTe SL has revealed, for the first time, that three subbands are occupied in this type-III system. We have found that m^*/m for the $i=2$ subband is roughly five times larger than m^*/m for $i=3$ subband although the $i=2$ and $i=3$ subbands are close together in energy. We are currently investigating diamagnetic SdH oscillations in the $B_\parallel$ configuration to check the self-consistency of our results and also determine the spatial extent of the wave functions.

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