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<sup>24</sup>It is unlikely that these defects are polarons since polaron formation would require the combination of two like-charged solitons, which would repel each other.

## Spin Superlattice with Tunable Minigap

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(Received 19 July 1982)

A "spin superlattice" can be formed by periodical doping with paramagnetic ions, so that only the effective  $g$  factor of the conduction electrons is affected. An external magnetic field and temperature therefore provide a suitable control for the modulation amplitude of the potential and hence for the resulting minigap.

PACS numbers: 73.40.Lq, 75.20.Hr

Superlattices are periodically arranged layers of semiconductor materials having different energy-band parameters with a periodicity much greater than the fundamental lattice constant.<sup>1</sup> The superlattice periodicity leads to the formation of different subbands separated by minigaps. The energy position of the subbands and the width of the gaps depend directly on the effective superlattice potential. Up to now the parameters of this potential were essentially set during the growing process of the superlattice, usually by molecular-beam epitaxy. Afterwards only minor changes could be obtained by space-charge effects.

I propose now a completely novel kind of superlattice based on semimagnetic semiconductors. The effective superlattice potential can be tuned from zero to a saturation value depending on the external magnetic field, the temperature, and the "spin doping" of the material. In addition, the superlattice potential is approximately of the square-well type, so that from the theoretical point of view a corresponding simulation is most easily performed.

In a recent Letter we pointed out that spin doping by paramagnetic ions affects essentially the electronic  $g$  factor of a semiconductor, whereas all other energy-band parameters can be well approximated by the values of the undoped material.<sup>2</sup> Spin doping is easily achieved by substitution of only a very small amount of crystal constituents by paramagnetic ions. It is well known that for such a semiconductor  $A_{1-x}M_xB$ — $M$  indicating the paramagnetic substance—the effective

$g$  factor is of the following form<sup>3</sup>:

$$g = g_0 + xJ\langle S_z \rangle / \mu_B H. \quad (1)$$

Here  $g_0$  is the  $g$  factor of the undoped material,  $\mu_B$  is the Bohr magneton, and  $H$  is the external magnetic field.  $J$  describes the  $s$ - $d$  exchange coupling, and  $\langle S_z \rangle$  is the thermal average of the localized spins of the paramagnetic dopant along the magnetic field axis. The quantity  $\langle S_z \rangle$  is usually a very sensitive function of the temperature and therefore the temperature control provides a direct means of controlling the spin splitting. It should be noted that for very high temperatures the average polarization  $\langle S_z \rangle$  vanishes, so that in this limit the band structure merges into that of the undoped material.

Actually the above assumption that the energy gaps are only negligibly affected by spin doping is not quite correct. This shortcoming, however, can be easily overcome by the combination of two different mixed crystals  $A_{1-x}M_xB$  and  $A_{1-y}D_yB$  in the superlattice, where the concentrations  $y$  of the nonmagnetic dopant  $D$  are chosen in such a way that the energy gaps of both materials are the same. Such complementary materials are, for example,  $\text{Hg}_{0.99}\text{Mn}_{0.01}\text{Se}$  and  $\text{Hg}_{0.976}\text{Cd}_{0.024}\text{Se}$ , where only the manganese acts as "spin dopant," but the cadmium has no influence on the electronic  $g$  factor of the system.<sup>4,5</sup>

Such a periodic arrangement of  $A_{1-x}M_xB$ — $A_{1-y}D_yB$  double layers leads to a superlattice where only the electron  $g$  factor has a periodic spatial modulation, essentially a "spin super-

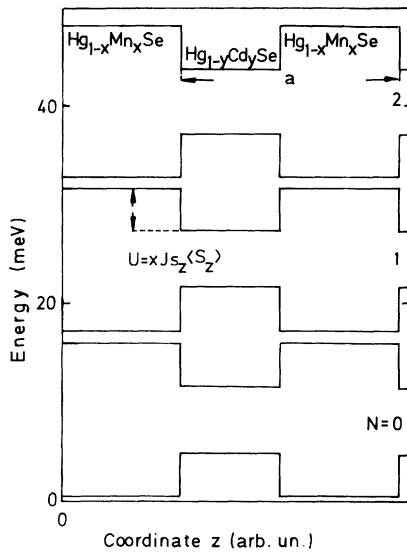


FIG. 1. In a  $\text{Hg}_{1-x}\text{Mn}_x\text{Se}-\text{Hg}_{1-y}\text{Cd}_y\text{Se}$  superlattice the motion perpendicular to the layers ( $z$  direction) is affected only by the spatial variation of the  $g$  factor, so that the amplitude  $U$  of the effective potential can be tuned by an external magnetic field and temperature. The parameters used are  $B=4$  T and  $T=1.8$  K.

lattice." For an external magnetic field,  $H$ , perpendicular to the layers, the effective Hamiltonian for the motion parallel to the field is given by the following expression:

$$\mathcal{H} = E_0 + \hbar\omega(N + \frac{1}{2}) + \mu_B g(z) s_z H + p_z^2 / 2m, \quad (2)$$

where the effective  $g$  factor is a function of the coordinate  $z$ . I would like to point out again that the band edges  $E_0$  have been set equal for both superlattice components. The effective potential for the motion in the  $z$  direction is of the square-well type and its amplitude is determined only by the variation of the  $g$  factor:

$$U = \Delta g \mu_B s_z H = x J s_z \langle S_z \rangle. \quad (3)$$

The polarization  $\langle S_z \rangle$  can be continuously tuned from zero to its saturation value by both the magnetic field and the temperature. For very high temperature  $\langle S_z \rangle$  vanishes so that the periodic superlattice arrangement becomes a homogeneous medium for the conduction electrons. It should be noted that for "spin-up" and "spin-down" states the effective potential has reversed modulation.

In Fig. 1 I have plotted the effective potential attached to the different spin-split Landau levels for electrons in a  $\text{Hg}_{0.99}\text{Mn}_{0.01}\text{Se}-\text{Hg}_{0.976}\text{Cd}_{0.024}\text{Se}$  superlattice. Despite the small spin doping of only 1%, the potential amplitude has a value of

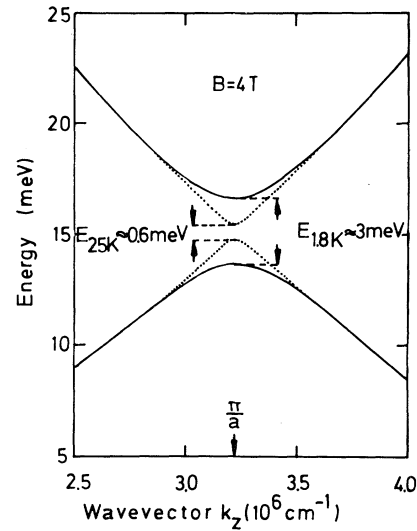


FIG. 2. The minigap at the zone boundary of a  $\text{Hg}_{0.99}\text{Mn}_{0.01}\text{Se}-\text{Hg}_{0.976}\text{Mn}_{0.024}\text{Se}$  spin superlattice can be tuned from 0.6 to 3 meV by decreasing the temperature from 25 to 1.8 K, respectively.

about  $U = 4.4$  meV as extrapolated from our previous data.<sup>2</sup> The magnetic field has been assumed to be  $B = 4$  T and the temperature  $T = 1.8$  K. For higher spin doping the potential amplitude should be correspondingly increased.

For such a superlattice with layers of equal thickness and a superlattice constant  $a \approx 97$  Å—equivalent to 16 fundamental lattice cells—I have plotted in Fig. 2 the Kronig-Penney energy-wave-number relation near the boundary of the superlattice Brillouin zone as indicated by the vertical arrow at about  $k_{Br} = 3.22 \times 10^6 \text{ cm}^{-1}$ .<sup>6</sup> At the zone boundary we obtain clearly a minigap, which can be tuned externally by temperature. The value of the minigap is of that order of magnitude that submillimeter spectroscopy is applicable for the investigation of interminigap transitions. For this purpose the external magnetic field should be tuned in such a way that the Fermi energy lies within one of the minigaps attached to the different Landau levels.

From the technical point of view the growing of spin superlattices using semimagnetic materials should not encounter too large difficulties, because the lattice constants of both semiconductor materials are equal within 10<sup>-2</sup>%.<sup>7</sup> I do hope that the experimental realization of the spin superlattice by molecular-beam epitaxy will be strongly stimulated by this Letter, so that its interesting features can be corroborated by many different experimental techniques.

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## Photogenerated Gap States in Polyacetylene

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(Received 4 March 1982)

This paper reports the first observation of photogenerated gap states in polyacetylene,  $(\text{CH})_x$ . A transient optical absorption, at photon energies less than the band gap, is produced by photogeneration of electron-hole pairs. The spectrum of this absorption is measured in both *cis* and *trans* isomers of  $(\text{CH})_x$ . From a comparison of these spectra with similar spectra seen in molecular analogs of  $(\text{CH})_x$ , it is concluded that these gap states are intrinsic, self-localized excitations of the semiconductor chain.

PACS numbers: 71.38.+i, 72.80.Le, 78.50.Ge

The ability to synthesize polyacetylene,  $(\text{CH})_x$ , in bulk or thin-film form<sup>1</sup> has inspired interest in the physics of a one-dimensional (1D) organic semiconductor. Of particular interest is the nature of electronic excitations responsible for charge and energy transport along the chains. Theoretical studies<sup>2-8</sup> of 1D models of  $(\text{CH})_x$  indicate that the lowest-energy electronic excitations are not free electrons and holes, but rather are self-localized states which have energy levels in the gap. Remarkably, the effective masses of these states, with their associated lattice distortions, are comparable to the free-electron value and therefore their in-chain mobility can be high.

In  $(\text{CH})_x$  the chain consists of a backbone of carbon atoms in a planar structure with alternating single and double bonds between them (see Fig. 1). The mobile distortion of this structure which has been discussed most extensively is a boundary between two segments of chain which differ by  $\pi$  in the phase of their bond alternation. Associated with this kink, or "soliton," is an electronic level of nonbonding character, located at the gap center. The most significant prediction of a simple 1D, one-electron model of  $(\text{CH})_x$ , first described by Su, Schrieffer, and Heeger,<sup>3</sup> and by Rice,<sup>4</sup> is that in *trans*- $(\text{CH})_x$  a pair of injected carriers is unstable to the formation of a pair of these mid-gap levels.

Generation of solitons has been invoked<sup>3,9</sup> to ex-

plain the unusual and dramatic effects of doping the polymer with strong oxidizing and reducing agents. However, the carrier added to the chain by this procedure is tightly bound to the dopant ion and may not represent an unperturbed excitation of the polymer chain. To attempt to create intrinsic gap states we have used photoexcitation to add electron-hole pairs to  $(\text{CH})_x$ . We find that a transient optical absorption, at photon energies less than the band gap, is produced by photoexcitation. From a comparison of the spectrum of this transient absorption with similar spectra seen in molecular analogs of  $(\text{CH})_x$ , we conclude that the gap states we observe are the intrinsic, self-localized excitations of the  $(\text{CH})_x$  chain.

The samples for this experiment were prepared according to the procedure first described by Ito, Shirakawa, and Ikeda.<sup>1</sup> The *cis*- $(\text{CH})_x$  samples, polymerized at 196 K onto fused silica cover slips, were transferred directly to the cold cryostat. The *trans*- $(\text{CH})_x$  was obtained from the as-grown *cis* isomer by a heat treatment of 180°C for 2 min. The thickness of the samples was  $\sim 1000 \text{ \AA}$ .

In order to measure the transient optical absorption due to the excited state, a tungsten-halogen lamp and monochromator were used to provide a variable-wavelength probe beam. The  $(\text{CH})_x$  was photoexcited by a 10-Hz train of 10-ns pulses from a dye laser tuned to 2.2 eV, near the peak of the