effect in a maser. (4) The transition-probability matrix elements calculated¹² for ruby [see Fig. 2(b)] show an increase near the minimum energy separation, as does the emitted power upon approaching the minimum frequency in the present case (Fig. 1).

Neither the precise nature of the states nor the mechanism pumping them has been established. One possible pumping mechanism is that noted by Clark and Feher¹³ in studies of the effect of drift current on nuclear magnetic resonance in InSb. In their experiments the sign of the g factors in the contact material and in the InSb semiconductor ($g_{InSb} = -56$) are opposite, which means that those electrons which are injected from the contact into the InSb and do not undergo a spin-flip transition will find themselves at a negative spin temperature. They found evidence of a negative polarization (but not necessarily negative temperatures) in the neighborhood of the negatively biased contact. This mechanism, while unproved in the present case, is in agreement with the observation that the contacts play an important role and that the radiation is probably emitted at or near the contacts.

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SIMPLE BAND MODEL FOR AMORPHOUS SEMICONDUCTING ALLOYS*

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Because of the near perfect local satisfaction of the valence requirements of each atom, which is complemented by the positional and compositional disorder, covalently bonded amorphous alloys are intrinsic semiconductors. We describe a band model with some novel features, which successfully describes several important effects observed in these amorphous semiconducting alloys.

Amorphous covalent alloys particularly of group-IV, -V, and -VI elements are readily formed over broad ranges of composition.¹⁻⁶ They have been described as low-mobility electronic intrinsic semiconductors with a temperature-activated electrical conductivity $\sigma = \sigma_0$ $\times \exp(-\Delta E/kT)$ which sometimes extends well into the molten state.^{2,3,7} They remain intrinsic

with changed ΔE when their composition is changed.^{1,5,7} These alloys transmit infrared light up to an exponential absorption edge from which an energy gap E_g is estimated.^{1,2} The value of E_g usually is smaller than $2\Delta E$, often by as much as 10-20 %.^{7,8} Photoconductivity⁹ and recombination-radiation¹⁰ measurements have been interpreted as giving evidence for the presence of localized states in the gap.

This Letter describes a simple band model based on the common features of the covalent amorphous alloys which is able to explain many of their properties. Among the novel features of the model are overlapping conduction and valenceband tails of localized states and sharp mobility edges.

We suppose that in these alloys most atoms are in sites satisfying their valence requirements.¹¹ This leads to the notion of a valence band of extended states despite the randomly differing valences of the constituent atoms and to an energy separation between valence- and conduction-band states corresponding roughly to an energy for breaking valence bonds. However, there is compositional disorder, and the translational disorder is enhanced over that in an elemental or compound glass because the coordination number varies from site to site to accommodate the varying valences of the atoms. One therefore expects a high density of localized states tailing in from the conduction and valence bands, as shown in Fig. 1(a).¹² By a localized state, we mean one with probability amplitude decreasing exponentially with distance from the center of localization for sufficiently large distance. The fluctuations in potential on the atomic scale caused by the disorder give rise to these localized states. There may be more than one localized state associated with a given large potential fluctuation. In general, only one such state can be occupied at a time; double occupancy may occasionally be possible.

In our model of amorphous alloys, the tails of the valence and conduction bands overlap, which means that an electron in a valence band in some region of the material may have a higher energy than an extra electron in a nonbonding state in another part of the material. Such electrons from the top of the valence-band tail fall into spatially distinct states in the lower conductionband tail. The Fermi level $E_{\rm F}$ thus falls near the center of the "gap" where the total density of states is near its minimum.

Conduction-band states are locally neutral when



FIG. 1. Sketch of (a) the partial densities of states of the valence and conduction bands and (b) the electron and hole mobility, respectively. The units of the ordinates are indicated as arbitrary because no quantitative calculation has been made. States which are neutral when occupied are associated with the valence band, the others with the conduction band; they overlap in the mobility gap.

unoccupied, and valence-band states are locally neutral when occupied by an electron. The empty valence-band tail states therefore give rise to a random distribution of localized positive charges neutralized on the average by a corresponding distribution of an equal number of localized negative charges which are associated with the occupied conduction-band tail states. The resulting Coulomb potential fluctuations of course alter the energies of all states so that the occupancy of the tail states has to be considered self-consistently. These charged states above and below $E_{\rm F}$ act as efficient trapping centers for electrons and for holes, respectively.

We suppose that the transition from extended band states to localized gap states would occur at an energy E_v for the valence band and E_c for the conduction band if it were not for the spatially varying electrostatic potential V caused by the density N of randomly distributed charged gap states. Ignoring V, we would expect the mobility to drop sharply at E_c and E_v as shown in Fig. 1(b). At these mobility edges, the conduction process changes from a low-mobility band transport with finite mobility at T=0 to a thermally activated hopping¹³ between localized gap states which disappears at T=0.

A possible interpretation of the low, temperature-independent Hall mobility¹⁴ is that the mean free paths in those portions of the bands of extended states relevant to transport is of the order of the interatomic separation in these materials. The mean free path is the distance over which the phase coherence of the wave functions extends, and we take it to be small compared to the distance over which V varies, $N^{-1/3}$ or 45 Å for $N = 10^{19}$ cm⁻³. V is therefore locally constant and the band model depicted in Figs. 1(a) and 1(b) applies locally except that E_v and E_c fluctuate together relative to E_F by $\delta E \approx 2e^2 N^{1/3}/\epsilon$, or 0.1 eV for $N = 10^{19}$ cm⁻³ and a dielectric constant ϵ of 10.

This band model correlates and is supported by a variety of observations.

The presence of the "mobility edges" near E_c and E_n explains why a well-defined activation energy ΔE is observed for σ despite the lack of sharp band edges. A further elaboration of the model permits us to estimate $2\Delta E$ to be about $(E_c - E_v) + 2\delta E$ and somewhat larger than $E_g < E_c$ $-E_v$. A conduction showing an activation energy significantly lower than E_g has been observed to set in at lower temperatures.¹⁵ This conduction is believed to be phonon-assisted hopping near $E_{\mathbf{F}}$ rather than band conduction by carriers excited from shallow donor or acceptor levels because its magnitude is very sensitive to minor heat treatments. Furthermore, measurements of electron tunneling from a metal through an oxide barrier layer into an amorphous semiconductor show¹⁶ that $E_{\mathbf{F}}$ remains near the gap center as T is lowered from 300 to 78°K. From the magnitude of the low-temperature hopping conduction and from the change in conductivity which results when a thin film of amorphous semiconductor is charged as in an insulated-gate field-effect transistor, one can estimate the density of gap states near the Fermi level. A value $g(E_F) \sim 6 \times 10^{19}$ cm⁻³ eV⁻¹ was obtained for a chalcogenide glass of composition $Te_{0.5}As_{0.3}Si_{0.1}Ge_{0.1}$ for which ΔE =0.45 eV. This magnitude for $g(E_{\rm F})$ is consistent with a magnitude for N of 10^{19} cm⁻³. Deviations from the local satisfaction of valence requirements are unimportant until of order N.

A gap state density of this magnitude agrees with the observation that blocking or rectifying Schottky barriers do not appear to exist at contacts of any metal with an amorphous covalent alloy.¹⁷ This model predicts space charge layers sufficiently thin for carriers to tunnel through easily, their thickness being roughly $(4\pi g e^2/\epsilon)^{-1/2}$, or ~30 Å with a dielectric constant ϵ of 10.

The recombination radiation¹⁰ observed at 78°K in vitreous $As_2Te_3 \cdot As_2Se_3$ at 78°K shows a weak peak at 1.16 eV and a strong peak at 0.67 eV. The first is clearly due to interband recombination. We attribute the stronger low energy peak to the efficient capture of carriers by the charged electron and hole traps near E_F .

The decay of photoconductivity after electronhole pair-producing illumination shows a fast and slow component.^{9,18} The long relaxation time can be hours at low temperatures, leading to a photostimulated excess conductivity which can be orders of magnitude larger than the conductivity prior to illumination. A similar excess conductivity can be stimulated at low temperatures by a transient increase of the electric field into the non-Ohmic range.¹⁸ Such a stored and presumably trap-activated conductivity appears to contradict a model with a large number of recombination centers distributed throughout the gap. However, as pointed out above, the electron traps are predominantly above $E_{\mathbf{F}}$ and the corresponding hole traps below $E_{\rm F}$. The initial rapid decay of the photoconductivity we attribute to the capture of carriers by the high density of traps below (or above for holes) the mobility edges. Nonequilibrium distributions of electrons and holes are thereby established leading to the observed excess conductivity. The long relaxation time is governed by their decay towards equilibrium via the slow processes of hopping and of capture of carriers by deep traps.

This band model is probably inadequate for elemental and compound amorphous semiconductors on the one hand and for molecular amorphous solids with large band gaps on the other. In the former case, there are likely to be welldefined structural defects leading to localized states of well-defined energy, contradicting the monotonic variation of g with E we have supposed to occur in the tails, and moving the Fermi energy out of the middle of the gap. Examples for the latter case are silicon oxide and solutions of metal in liquid ammonia¹⁹ in which dissolved atoms neither are incorporated in nor greatly change the principal molecular units which make up the amorphous material and hence may give rise to donor or acceptor states within narrow energy regions of the gap.

This band model does not resolve the dilemma of the positive thermopower versus the negative Hall coefficient observed in covalent alloy glasses, 3,14,20,21 nor does it explain the magnitude of the density of band states near the mobility edges which is needed to explain the magnitude of the factor σ_0 in the conductivity. 12,22,23

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QUANTUM STATISTICS OF ONE-PHOTON INTERACTION OF LIGHT WITH MATTER

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Quantum statistics of one-photon interaction of light with matter is investigated. It is found that in general the density operator changes. For a chaotic field, however, the density operator changes only in a trivial way.

Quantum statistics of nonlinear interactions of light with matter has recently been investigated.^{1,2} In nonabsorbing media, one-photon interactions obviously do not change the photon statistics. Shen¹ has shown that if the incident radiation resonates with the atoms of the medium, the density operator changes in a trivial fashion and the nature of the radiation remains the same. In this paper, we report the results of our investigations of change in density matrix in one-photon interactions. The evaluation of the density matrix is simple and can easily be extended to two- or more-photon interactions. We find that in general the density matrix changes in a nontrivial way. Coherent light does not remain coherent and the photon fluctuations increase. The chaotic light, as a special case, however, remains chaotic.

Lambropoulos,² while discussing statistics of the two-photon amplifier, found the density matrix by considering the matrix element in occupation number space for the field, and solving the difference-