LOCALIZED VIBRATIONS OF PHOSPHORUS AND ALUMINUM IMPURITIES IN GaSb

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Reviews of the thoery of localized vibrations of light atomic impurities in crystals have been given recently.[1-3] In the case of insulating crystals, experimental investigations have been largely confined so far to the vibrations of H⁻ and D⁻ ions in the alkali halides[4,5] and the alkaline earth fluorides.[6] In the case of semiconducting crystals, particular attention has been given to boron impurities in silicon.[7-9] Localized vibrations of phosphorus and aluminum impurities in GaSb are described here.

The investigation by infrared methods of localized vibrations of electrically active impurities in semiconductors is made difficult by the associated free-carrier absorption; the free carriers may be removed by counterdoping with other impurities, by electron bombardment, or by a combination of both.[8] Al impurities in GaSb are expected to replace Ga atoms and P impurities are expected to replace Sb atoms, and since the valence structures are the same in both cases the free-carrier problem does not arise. However, high-purity GaSb has residual acceptors of unknown origin which introduce levels into the crystal with threshold energies at[10] about 250 cm^{-1} and 500 cm^{-1}; these occur with concentrations of $\sim 10^{17}/cm^3$ and compensation of the crystals is essential for the investigation of localized vibrational modes of dilute impurities in the region 300-350 cm^{-1}. Our crystals were grown with both the light impurity and the compensating agent tellurium added to the melt. A spectrochemical analysis of the specimens investigated showed aluminum present at 0.20% molar concentration; the phosphorus concentration could not be determined spectrochemically but is expected to be somewhat less than that of aluminum.

The localized-mode spectrum of phosphorus was measured at room and liquid-nitrogen temperatures (Fig. 1) with a grating monochromator. The background absorption is due to incomplete compensation and to the presence of a GaSb combination band which extends from 320 to 380 cm^{-1}. The spectrum of aluminum at liquid-nitrogen temperature is shown in Fig. 2; in this case compensation is less complete and the
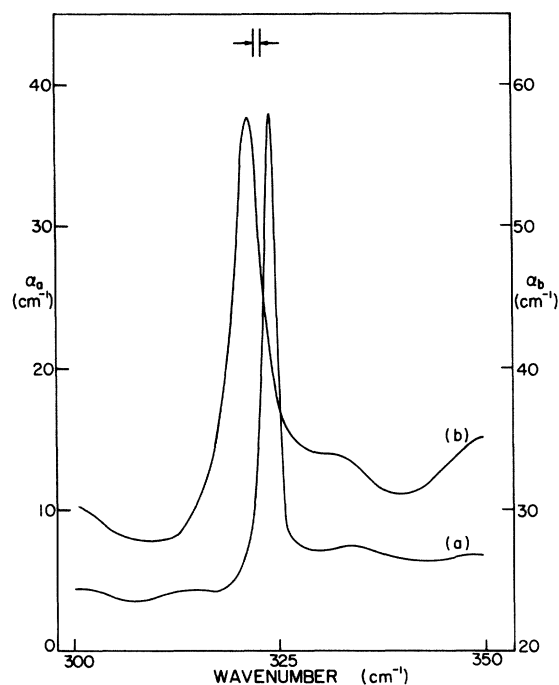

FIG. 1. Absorption coefficient α of the localized vibrational mode of phosphorus impurities in GaSb at (a) liquid nitrogen and (b) room temperature. The left ordinate is associated with curve (a) and the right ordinate with curve (b).
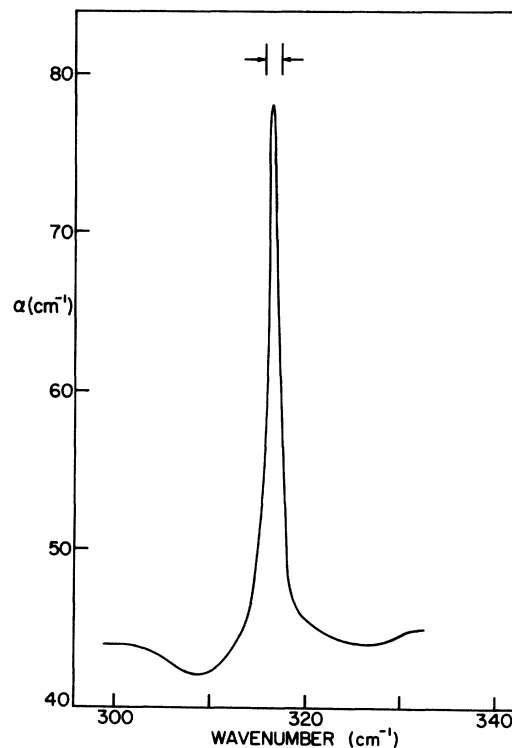

FIG. 2. Absorption coefficient α of the localized vibrational mode of aluminum impurities in GaSB at liquid-nitrogen temperature.

room-temperature curve has not been given be-
cause the low transmission of the sample made
measurements of α very inaccurate in the vicin-
ity of the peak.

When considering localized modes we shall,
as a first approximation, assume the host lattice
to be static. The impurity ion vibration is not
harmonic and for T_d symmetry (the point sym-
metry of substitutional sites in GaSb) the poten-
tial expanded to fourth order in the displacement
of the impurity is[6]

$$V = V_0 + A(x^2 + y^2 + z^2) + B(xyz)$$
$$+ C_1(x^4 + y^4 + z^4) + C_2(x^2y^2 + y^2z^2 + z^2x^2). \quad (1)$$

The vibrations of the host lattice add terms to
(1) coupling localized and band modes.[6,11] Be-
cause of the anharmonic terms in (1), one $n = 0$
$\rightarrow n = 2$ and two $n = 0 \rightarrow n = 3$ overtones of the local-
ized vibrations are allowed and have been ob-
served in the case of H$^-$ and D$^-$ ions in CaF$_2$.[6]

The transverse optical (TO) ($\vec{k} = 0$) frequency
for GaP occurs at 368 cm^{-1},[12] for AlSb at 319
cm^{-1},[13] and for GaSb at[14] 230 cm^{-1}; we may com-
pare the localized mode frequencies with these
frequencies since an investigation of the lattice
combination bands in the case of GaP[12] and
AlSb[13] indicates that the dispersion of the TO
frequencies is relatively small. The fact that
the fundamental ($n = 0 \rightarrow n = 1$) of the localized vi-
bration of phosphorus in GaSb (see Table I) is in-
termediate between the TO frequency of GaP and
GaSb is not surprising since the tetrahedral co-
valent radius[15] of P (1.10 Å) is less than that of
Sb (1.36 Å). However, the tetrahedral covalent
radius of Al (1.26 Å) is identical with that of
Ga [the lattice constants of AlSb (6.12 Å) and
GaSb (6.13 Å) are almost identical]. We there-
fore expect that the localized-mode frequency of
Al in GaSb (314 cm^{-1} at room temperature)
should be close to the TO frequency of AlSb
(319 cm^{-1}) and the agreement is striking.

Both P and Al have only one stable isotope
and in each case only one line is observed. The
fundamental ($\Gamma_1 \rightarrow \Gamma_4$) has a threefold spatial de-
generacy in the cubic environment and the sharp-

ness of the localized mode (see Table I) shows
that in both cases the cubic symmetry at the im-
purity site is preserved; in the case of Al at
liquid-nitrogen temperature the linewidth is
limited by the slit width (2 cm^{-1}). Localized vi-
brations of lithium impurities in GaAs have also
been investigated.[16] Association of the Li impur-
ities with other lattice defects occurs and the de-
generacy of the fundamental is raised; in this
case the localized-mode spectrum gives detailed
information about point-defect configurations in
the crystal.

A search in the vicinity of 650 cm^{-1} for the n
$= 0 \rightarrow n = 2$ overtone of the phosphorus vibration
was unsuccessful and indicated that the value of
α for this transition was at least a factor of 30
less than that of the fundamental. The observed
ratio of the values of α for these transitions in
the case of H$^-$ in CaF$_2$[6] was ~1/25; the $n = 0$
$\rightarrow n = 2$ transition is allowed because of anhar-
monicity and the intensity relative to the funda-
mental is expected to be smaller in the present
case because of smaller vibration amplitudes.

The linewidth of the localized modes is expected
to increase with temperature because of the scat-
tering of band modes off the defect.[6,11] The cou-
pling of the localized and lattice modes also gives
rise to a shift in peak position of the lines with
temperature.[6] The change with temperature of
the peak positions and widths of the lines should
be comparable,[17] and this is found to be so in the
present case (see Table I). Very little change in
the integrated absorption $\int \alpha(\nu)d\nu$ of the localized
mode should occur with change in temperature
and we find this to be the case with phosphorus
within the precision of our measurements. A de-
tailed discussion of the effects of temperature
on the peak position, width, and intensity of local-
ized vibrational modes is in course of prepara-
tion.[18]

Table I. Parameters of the localized mode spectra of P and Al impurities in GaSb.

| Temperature | Phosphorus | | Aluminum | |
	Peak positon (cm^{-1})	Linewidth (cm^{-1})	Peak position (cm^{-1})	Linewidth (cm^{-1})
Liquid nitrogen	324.0 ± 0.3	2.0	316.7 ± 0.3	<2.0
Room	321.4 ± 0.5	3.6	313.8 ± 0.5	...

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# EVIDENCE FOR A $T = 2$ $\Sigma\pi$ RESONANCE

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(Received 20 July 1964)

Since the discovery of the $Y_1^*(1385)$, there has been continuous speculation concerning the existence of a pion-hyperon resonance with isospin $T = 2$, but experiments to date have failed to find any evidence for its existence.[1,2] To further this investigation, we studied the reaction

$$K^- + n(C) \rightarrow \Sigma^- + \pi^- + \pi^+ + \text{recoils} \qquad (1)$$
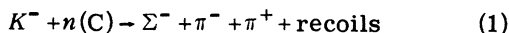
in a 1.15-BeV/c K^- interaction on neutrons in carbon in the Berkeley 30-in. propane chamber. The reaction

$$K^- + n(C) \rightarrow \Sigma^+ + \pi^- + \pi^- + \text{recoils} \qquad (2)$$
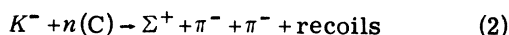
does not give any information concerning any $T = 2$ resonance, but has been studied for completeness. We also studied the reaction

$$K^- + p(C) \rightarrow \Lambda + \pi^- + \pi^+ + \text{recoils} \qquad (3)$$
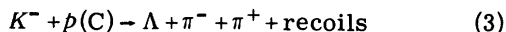
to see how a well-known resonance is produced in carbon.

For the charged pionic decays, the scan-table identification of sigmas depended completely on the ionization change at the decay point. This criterion did not bias against higher momentum sigmas,[3] but did give a bias against events where the pion track from the sigma decay was steep in the chamber. A total of 330 events of the type (1) was found in our scanning. The lifetime measured for Σ^- from the events $[(1.12 \pm 0.20) \times 10^{-10}$

sec] agrees with the accepted value.

The pion tracks involved in this experiment were generally long, and the momenta were determined by curvature measurements to approximately 12% on the average. However, the average sigma track length was 1.1 cm, and only a minimum value of the momentum could be obtained from range measurements. The angle of decay and the pion momentum were used to calculate the momentum of the sigma at the decay point. About half of the time, this resulted in solutions that were double-valued corresponding to forward or backward decay of the sigma in the center-of-mass (c.m.) system. For most of these events, ionization of the sigma was used to resolve this ambiguity. For the few cases where the ambiguity was not resolved by sigma ionization, the two solutions were equal within the errors, and the average value was used. The range-momentum relationship was then used to find the sigma momentum at the production vertex, but no constraints were applied at this point.

To observe resonances in the invariant-mass plot, we needed to know the phase space involved. Since, in our case, we had a variable c.m. energy available due to the Fermi momentum of the nucleons in the carbon nucleus, we adopted the following procedure to calculate the phase space: