Native defect related optical properties of ZnGeP₂

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We present photoluminescence, photoconductivity, and optical absorption spectra for ZnGeP₂ crystals grown from the melt by gradient freezing and from the vapor phase by high pressure physical vapor transport (HPVT). A model of donor and acceptor related subbands in the energy gap of ZnGeP₂ is introduced that explains the experimental results. The emission with peak position at 1.2 eV is attributed to residual disorder on the cation sublattice. The lower absorption upon annealing is interpreted in terms of both the reduction of the disorder on the cation sublattice and changes in the Fermi level position. The n-type conductivity of ZnGeP₂ crystals grown under Ge-deficient conditions by the HPVT is related to the presence of additional donor states. © 1994 American Institute of Physics.

Zinc germanium phosphide is a chalcopyrite structure semiconductor with a minimum pseudodirect band gap of ~2.1 eV at room temperature. It has a relatively large second-order susceptibility tensor component \( d_{36} = 75 \text{ pm/V} \) and an attractive transparency range extending from 0.67 to 13 \( \mu \text{m} \). In view of its substantial birefringence of 0.36\%, ZnGeP₂ is thus suitable for phase-matched nonlinear optical applications in the infrared, e.g., the fabrication of optical parametric oscillators and harmonic generation/sum frequency mixing based on powerful infrared laser sources.

In addition, ZnGeP₂ is of interest in the context of nearly lattice-matched heteroepitaxy of compound semiconductors on silicon.

The phase relations in the ternary system Zn, Ge, P are documented on the ZnP₂-Ge pseudobinary, indicating a congruent melting point at composition ZnGeP₂. ZnGeP₂ single crystals have been grown from the melt by the gradient freezing and horizontal Bridgman methods. Recently we have reported the growth of ZnGeP₂ crystals by high pressure physical vapor transport and the heteroepitaxial organometallic chemical vapor deposition growth of ZnGeP₂ on GaP and Si substrates, respectively.

ZnGeP₂ crystals grown from the melt are semi-insulating \((\rho=10^6 \Omega \text{ cm})\) and exhibit p-type conductivity. The carrier mobility in such crystals is 10 cm²/V s at a net acceptor concentration of \( 10^{10} \text{ cm}^{-3} \) suggesting a high compensation level \((10^{19} \text{ cm}^{-3})\). ZnGeP₂ crystals grown by metalorganic chemical vapor deposition and high pressure physical vapor transport (HPVT) are low resistivity p type and high resistivity n type, respectively. In the optical absorption spectra at room temperature bands at 1.31, 1.46, 1.58, 1.67, and 1.80 eV are observed. Annealing of the crystals for 300 h at 500 °C was found to be effective in reducing the residual absorption in the 0.67–3 \( \mu \text{m} \) region. Polarized photoluminescence (PL) and cathodoluminescence studies revealed bands in the 1.3–1.4 and 1.6–1.7 eV region, which were assigned to transitions between conduction bands states and a deep triplet acceptor band.

PL studies extending over the visible and infrared wavelength range (500–1700 nm) reveal, independent of the method of growth, a broad emission band with peak position at 1.2 eV. The luminescence was detected with a GaAs photomultiplier tube (PMT) and a Ge detector, being cooled with liquid nitrogen and having cutoffs at ~1.2 and 0.7 eV, respectively. This combination of detectors is essential since, due to the cutoff at 1.2 eV, the use of the PMT results in a false peak position of the infrared luminescence near 1.3 eV. Figure 1 shows typical PL spectra for (a) ZnGeP₂ platelets grown from the melt by the HPVT and (b) ZnGeP₂ crystals grown by high pressure vapor transport.
grown by the HPVT method and (b) ZnGeP₂ cut from a bulk single crystal grown by the gradient freezing method. The structure near 0.9 eV is due to H₂O absorption. In the vicinity of the nucleation point, HPVT grown ZnGeP₂ crystals exhibit additional near-edge emission, which shifts toward the infrared upon continued growth. After prolonged periods of HPVT only the 1.2 eV PL remains. The PL of as-grown bulk single crystals is also dominated by 1.2 eV emission with a high energy shoulder extending to ~1.8 eV. Annealing of the crystal in vacuum at 500 °C for 400 h results in a substantial increase of the 1.7 eV emission relative to the 1.2 eV emission. In order to check as to whether or not the points defects that give rise to the higher energy emission are preferentially formed near the surface, we removed ~1 μm from the surface of the annealed crystal by etching, which caused a significant lowering of the PL near 1.7 eV.

Figure 2 shows a PC spectrum for the same bulk crystal in the as-grown state. The PC reveals subband-gap excitation extending to ~1.6 eV with three characteristic peaks at 2.5, 2.85, and 3.2 eV. Figure 3 shows the changes of the absorption coefficient in the transparency region of the same ZnGeP₂ crystal that occur in the course of the annealing at 500 °C. A significant reduction in the near-infrared absorption is observed.

Studies of the time dependence of the PL in the range 1.2–1.6 eV, which will be described in more detail in a forthcoming publication, reveal hyperbolic decay behavior. The decay time decreases toward higher energies. Upon increasing the limits on the time window, the time-resolved spectra of the broad emission band exhibit a shift of the high energy edge to lower energies. For a given time window the intensity of the high energy edge of the PL decreases with increasing temperature between 5 and 100 K.

Because of the hyperbolic decay of the PL, we interpret the steady state luminescence shown in Fig. 1 in terms of transitions between donor and acceptor states associated with energy subbands in the band gap of ZnGeP₂ that are shown in Fig. 4. The broad PL band, peaked at 1.2 eV, can be attributed to transitions between donor (D₁) and acceptor (A₁) states that are associated with subbands below the absorption edge having a center distance of 1.2 eV. Explaining the structure in the PC spectra by transitions between filled A₁ states and the conduction band edge (CBE), the highest filled A₁ state is associated with an energy eigenvalue of ~1.6 eV below the CBE. Since the width of the broad subband-gap luminescence is at least 1 eV, this places the lower edge of the A₁ subband close to the upper valence band edge (VBE).

Figure 5 shows a schematic representation of some of the point defects that may be generated upon deviation of the ternary compound composition from stoichiometric ZnGeP₂, e.g., Zn_, Ge[,], and P[] vacancies and the formation of various antisite defects. Note that specific deviations from stoichiometry within the homogeneity range about stoichiometric ZnGeP₂ merely establish the predominance of specific native point defects, but preclude neither the presence of other defects nor interactions with extrinsic point defects. Although the point defect chemistry is thus complex, hints for the predominance of certain defects are obtained by the analysis of the annealing behavior and the behavior associated with specific growth conditions. The growth tempera-
ture under the conditions of GF and HPVT is above the order-disorder transformation between the chalcopyrite and zinc-blende structures of ZnGeP₂ which occurs at \(-950\) °C. Thus residual disorder that is quenched-in during cooling may persist in a metastable state at room temperature. It corresponds to the simultaneous existence of nonequilibrium populations of Ge\(_{\text{Zn}}\) and ZnGe antisite defects.

In agreement with the suggestion of Rud and Masagutova\(^{11}\) we attribute the residual absorption in the transparency range of ZnGeP₂ to transitions from the A\(_1\) subband into the conduction band and the D\(_1\) donor band. From the extension of the absorption to \(\sim 5\) \(\mu\)m,\(^{13}\) we can conclude that the lower edge of the D\(_1\) band extends to \(\sim 0.30\) eV above the upper edge of the A\(_1\) band, placing the lowest states belonging to the D\(_1\) subband at \(\sim 1.30\) eV below the CBE. Thus, in the absence of other point defects, the Fermi level (FL) is pinned to a position between the A\(_1\) and D\(_1\) subbands in the lower half of the band gap of ZnGeP₂, explaining the high resistivity \(p\)-type conductivity. Of course, the presence of additional donors and acceptors that are unrelated to the D\(_1\) and A\(_1\) subbands can contribute to the residual absorption which may be due to both additional \(A-D\) transition pathways and the associated shift in the Fermi level that affects the concentrations of filled acceptor and unfilled donor states.

The transitions between filled A\(_1\) and empty D\(_1\) states do not contribute to the PC spectra because of the large effective mass in the D\(_1\) subband due the localization of the associated donor states. The above interpretation is reinforced by the time-dependent recombination behavior starting with fast high energy transitions related to \(D-A\) pairs in close proximity that are followed by a slower recombination at lower energies corresponding to larger separations between the localized \(D-A\) pairs.

There are at least three effects that must be considered in the interpretation of the annealing studies: (i) The reduction of quenched-in disorder, reducing the concentration of point defects, (ii) The shift of the FL position associated with this annihilation of defects, altering the population of the remain-

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**FIG. 5.** Schematic representation of native point defects that may be generated upon deviations from stoichiometric in the homogeneity range of ZnGeP₂.