Strong polarization of the photoluminescence of $In_xGa_{1-x}P$ grown on (110) GaAs

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Strong linear polarization of photoluminescence (PL) from $In_xGa_{1-x}P$ ($0.485<x<0.55$), grown by MOS-hydride epitaxy on (110) GaAs, has been observed. To explain the polarization of photoluminescence, a new type of ordering in $In_xGa_{1-x}P$ was hypothesized. In the ordered phase the In and Ga atoms occupy cation sites not randomly but rather in pairwise alternating $(\bar{1}10)$ planes. X-Ray crystallographic studies revealed superstructural reflections corresponding to a $(InP)_2(GaP)_2$ bilayer superlattice with a period of ~8 Å in the $[\bar{1}10]$ direction. This observation confirms our hypothesis. © *1995 American Institute of Physics.*

It is well known[1] that $In_xGa_{1-x}P$ ($x\approx0.5$), grown by the method of MOS-hydride epitaxy on (001) GaAs, contains inclusions of an ordered phase. In the ordered phase the In and Ga atoms occupy cation sites in the lattice not randomly but rather in alternate $(1\bar{1}1)$ or $(\bar{1}11)$ planes. As a result, the symmetry in these inclusions is lowered from cubic symmetry $F\bar{4}3m$ to trigonal symmetry $R3m$ and instead of a structure with a zinc blende lattice, a structure with CuPt-type lattice is formed.[2] Other types of ordering are also possible.[3,4] Since the ordered phase of $In_xGa_{1-x}P$ is optically anisotropic and its band gap is smaller than in the disordered solid solution, ordering in $In_xGa_{1-x}P$ leads to polarization of photoluminescence (PL). However, the degree of polarization of photoluminescence from the growth plane in such structures does not exceed 50%, because the planes of ordering are tilted by and angle of 55° with respect to the growth plane.

In our study we observed strong linear polarization of photoluminescence from $In_xGa_{1-x}P$ ($0.485<x<0.55$) grown by MOS-hydride epitaxy on (110) GaAs. The degree of polarization of the photoluminescence from the plane of growth is close to 100%. To explain the polarization dependence of the photoluminescence intensity, a new type of ordering in $In_xGa_{1-x}P$ was hypothesized. In the ordered phase the In and Ga atoms occupy pairwise alternating cation planes $(\bar{1}10)$. To check this hypothesis, we performed an x-ray structural analysis. We observed superstructural reflections corresponding to a $(InP)_2(GaP)_2$ bilayer superlattice with a period of ~8 Å in the $[\bar{1}10]$ direction. This observation confirms our hypothesis.

The $In_xGa_{1-x}P$ epitaxial layers ($x=0.485-0.55$) were grown at 650 °C at a rate of ~10 Å /s by the method of MOS-hydride epitaxy at atmospheric pressure. The sources

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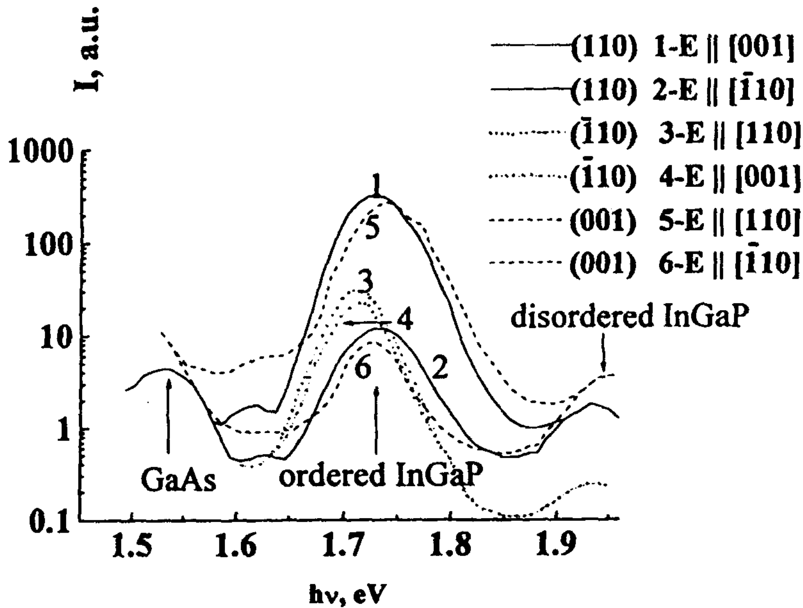

FIG. 1. Photoluminescence spectra from $In_{0.52}Ga_{0.48}P$ from three different faces for two different polarizations in each case: (110) — curves *1* (**E** || [001]) and *2* (**E** || [$\bar{1}$10]); ($\bar{1}$10) — curves *3* (**E** || [110]) and *4* (**E** || [001]), (001) — curves *5* (**E** || [110]) and *6* (**E** || [$\bar{1}$10]).

were trimethyl indium, trimethyl gallium, and phosphine. The layers were 0.8–2.2 μm thick, n and p type with a carrier concentration not exceeding 10^{17} cm^{-3}. The substrate consisted of n^+-GaAs (AGCHO-1). The epitaxial layers were grown on the (110) plane.

Two lasers were used to excite the photoluminescence: a 40-mW HeNe laser ($\lambda = 633$ nm) and a 1-W Ar laser ($\lambda = 514$ nm). The laser radiation was focused into a ~0.1-mm-diameter spot on the (110) face.

Figure 1 shows the photoluminescence spectra observed at 77 K from the (110), ($\bar{1}$10), and (001) faces of $In_{0.52}Ga_{0.48}P$ for two different polarizations in each case. The photoluminescence was always observed in a direction close to perpendicular to the face from which the radiation emerged. The long-wavelength peak in the spectra corresponds to photoluminescence from n^+-GaAs. Its intensity does not depend on the polarization. For convenience, the photoluminescence spectra corresponding to different directions of observation are displaced relative to one another along the ordinate. The middle peak ($\hbar\omega = 1.73$ eV) corresponds to luminescence from the ordered phase of the solid solution. The short-wavelength peak ($\hbar\omega = 1.94$ eV), just as the long-wavelength peak, depends weakly on the polarization. We assume that it corresponds to photoluminescence from the disordered solid solution. It is obvious from the figure that the photoluminescence, observed from the growth face, of the ordered solid solution (curves *1* and *2*) is strongly polarized. For $\hbar\omega = 1.73$ eV the photoluminescence peak corresponding to an electric field direction **E** || [001] (curve *1*) is approximately 1.5 orders of magnitude higher than the peak corresponding to **E** || [$\bar{1}$10] (curve *2*). At the same time, the photoluminescence

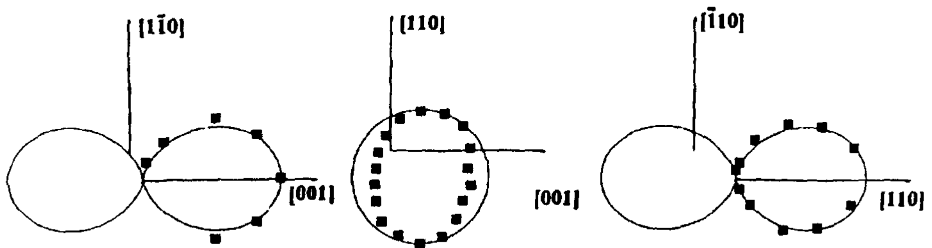

FIG. 2. Photoluminescence intensity as a function of the direction of the electric field vector. The figure on the left corresponds to photoluminescence from the (110) face, the middle figure corresponds to ($\bar{1}$10), and the figure on the right corresponds to (001).

from the ($\bar{1}$10) face is weakly polarized (curves *3* and *4*). The difference between curves *3* and *4* is due to the accuracy of the measurements of the photoluminescence intensity. Such a polarization dependence of the photoluminescence was observed for all experimental samples ($x=0.485-0.55$).

According to the theory of the optical properties of semiconductors with the sphalerite structure,[5] strong (100%) linear polarization of photoluminescence can occur in the case where the top of the valence band is formed by heavy-hole states with a distinguished direction of the quasimomentum **p**. This happens because radiative dipole transitions between the conduction band and the heavy-hole band are forbidden in the case $\mathbf{E} \parallel \mathbf{p}$. It is also known that the top of the valence band in quantum wells and superlattices is formed by hole states with quasimomenta in the direction of quantization of the motion (the direction of change of the potential for the envelope of the wave function).

These arguments lead us to two assumptions for explaining the polarization of the photoluminescence. The first one is that the top of the valence band in the experimental structures is formed by heavy-hole states. The second one is that a potential varying in the [$\bar{1}$10] direction appears for the envelope of the wave function. A potential of this kind can appear as a result of In and Ga atoms occupying alternate ($\bar{1}$10) planes, i.e., as a result of ordering in the [$\bar{1}$10] direction.

To check these assumptions, we measured the dependence of the photoluminescence intensity on the direction of **E** for three directions of observation. Figure 2 shows the results of these observations and the dependences computed on the basis of the assumptions presented above. It is obvious that good agreement is obtained between the experimental and theoretical curves.

To determine the type of ordering in the $In_xGa_{1-x}P$ layers grown on (110) GaAs, we performed an x-ray analysis of a ~ 2-μm-thick sample with $x \approx 0.52$ on a DRON-2 diffractometer (CuKα radiation). The ordering in the ($\bar{1}$10) planes simultaneously with the ordering along the (110) and (001) planes in the solid solutions is characteristic of CuAuI-type ordering. Such ordering has been observed in $Al_xGa_{1-x}As$ epitaxial layers grown on a (110) GaAs substrate.[6] In this type of ordering the planes containing only Al atoms alternate with planes containing only Ga atoms, i.e., a one-layer (AlAs)(GaAs) superlattice forms. The diffraction pattern of such a layer contains superstructural reflec-

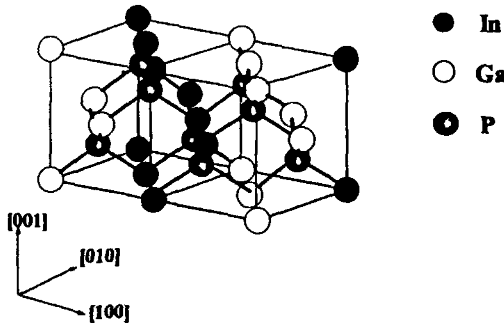

FIG. 3. Arrangement of atoms in the ordered phase of $In_{0.5}Ga_{0.5}P$.

tions with the indices $2n\pm 1$, $2n\pm 1$, $2n$ or $2n$, $2n$, $2n\pm 1$, which are forbidden in a disordered structure (sphalerite lattice).

Superstructural reflections with indices characteristic of CuAuI ordering were not observed. It was assumed that in the layer which we studied ordering according to a $(InP)_2(GaP)_2$ bilayer superlattice, when two neighboring $(\bar{1}10)$ planes containing only In atoms alternate with two planes containing only Ga atoms (see Fig. 3), is possible. For such ordering the diffraction pattern should contain superstructural reflections with the indices $h\pm 1/2$, $k\mp 1/2$, $\pm l$. We recorded the superstructural reflections $\frac{3}{2}\frac{1}{2}1$, $\frac{1}{2}\frac{3}{2}1$, $\frac{3}{2}\frac{1}{2}\bar{1}$, and $\frac{1}{2}\frac{3}{2}\bar{1}$, which confirm our assumption. Therefore, a $(InP)_2(GaP)_2$ bilayer superlattice with a period ~ 8 Å in the $[\bar{1}10]$ direction is formed in the experimental $In_xGa_{1-x}As$ layers grown on a (110) GaAs substrate.

In conclusion, we note that the energy of a radiative transition from the ordered phase of $In_xGa_{1-x}P$ ($\hbar\omega = 1.73$ eV) in our samples is less than the energy of radiative transitions from an ordered phase with a CuPt lattice ($\hbar\omega \approx 1.8$ eV), whereas in Ref. 3 the opposite relation between these energies was predicted on the basis of an analysis of similar ordering in the (110) plane.

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