Optical surface waves in periodic layered medium grown by liquid phase epitaxy[a]

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(Received 21 November 1977; accepted for publication 16 January 1978)

Optical surface waves propagating along the surface of a multilayer stack have been observed. The multilayer stack is grown by liquid phase epitaxy. The transverse intensity distribution measured is found to agree with our theoretical calculation.

PACS numbers: 42.82.+n, 68.55.+b, 42.80.Lt

Recent theoretical and experimental investigations[1-3] have demonstrated the possibility of using periodic layered media in guided wave optical applications. The experiments reported utilized GaAs-$Ga_{1-x}Al_xAs$ configurations grown by molecular beam epitaxy (MBE).

Many of the important GaAs devices which utilize guided wave configurations are commonly grown by liquid phase epitaxy (LPE). In addition, LPE growth rates are at least an order of magnitude faster than those of MBE. This has prompted us to attempt the growing of periodic layered media using GaAs and GaAlAs by LPE techniques. The growth techniques, the resulting layered structure, and the observation of an optical surface wave in this structure are reported in what follows. It is interesting to note that quantum size effects have also been observed recently in multiple thin layers grown by LPE.[4]

The periodic layered stack grown is shown in Fig. 1. It consists of 42 alternating layers $0.2\ \mu$m thick of GaAs and $Al_{0.2}Ga_{0.8}As$ grown by LPE on a GaAs substrate. The total growing time for this structure was $\sim$1 h. The multilayers were grown by standard horizontal sliding boat techniques. The growth substrate was placed between two dummy substrates in the horizontal slider. During the growth of the multilayers, the substrate was brought into contact with growth solutions of GaAs and $Ga_{0.8}Al_{0.2}As$ alternately by sliding it smoothly back and forth between the two solutions which were contained in adjacent bins of the graphite boat. The use of "dummy" substrates in front of and behind the real substrate kept the growth solutions and real substrate as close to equilibrium as possible. The steady cooling rate used during the layer growth was 0.2°C/min. The growth cycle was as follows: After equilibrium was attained by heating the solution for several hours, the first "dummy" wafer was brought into contact with the first (GaAs) solution for a cooling of 3–4°C. The "dummy" wafer was next pulled into contact with the second, now supercooled GaAlAs solution, to bring it into equilibrium. During this last interval a relatively thick first layer of GaAs formed on the growth substrate (shown in the SEM, Fig. 1, of the cleaved cross section). The growth substrate was next pulled back into contact with the GaAlAs solution to grow the first layer of the periodic medium which was a GaAlAs layer. Repeated sliding of the substrate between the two solutions led to the layered structure

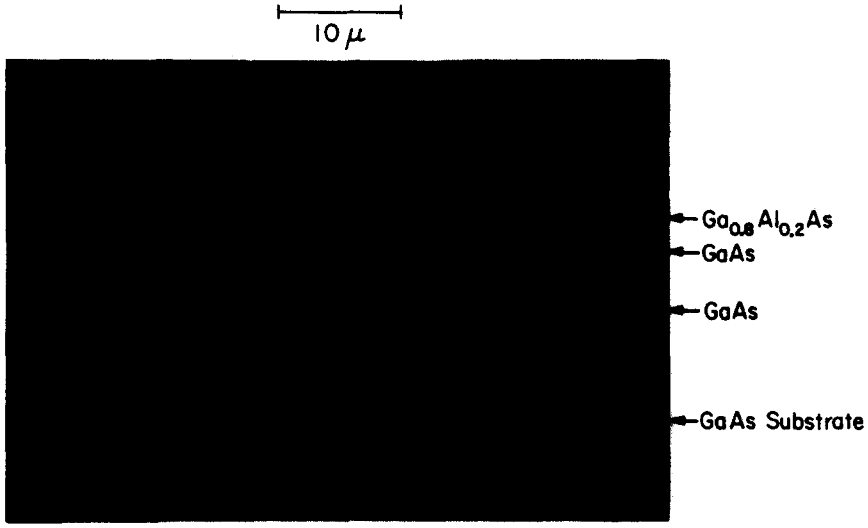

FIG. 1. A cleaved cross section of the waveguide consisting of 42 alternating layers of GaAs and $Al_{0.2}Ga_{0.8}As$ by SEM.

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[a] Research supported by the Office of Naval Research and the National Science Foundation.

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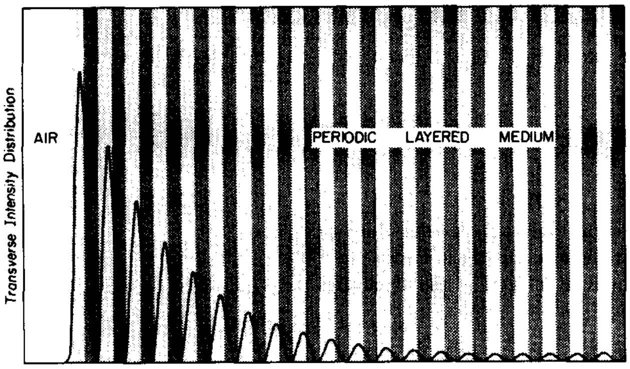

FIG. 2. Theoretical transverse intensity distribution of the surface wave with $(\omega/c)n_a < \beta < (\omega/c)n_1$ for a sample with layer thicknesses corresponding to that shown in Fig. 1.

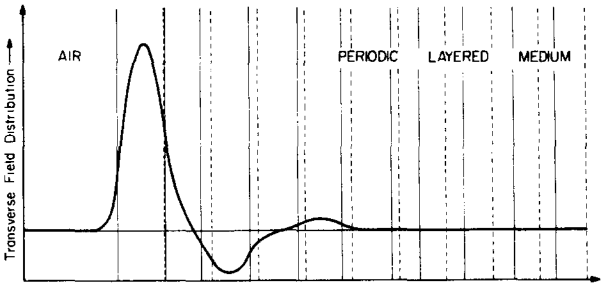

FIG. 4. Calculated transverse field distribution of a surface wave in an imperfect periodic layered medium with a standard deviation from perfect periodicity of 20%. The dotted lines indicate layer boundaries for a perfectly periodic medium.

growth. At any one time the idle solution was equilibrated (i.e., kept at equilibrium) by one of the two "dummy" substrates. Wipe-off problems were minimized by winding molybdenum wires around the graphite boat so that the clearance between the wafers and slot was minimized.

The theoretical intensity distribution for the lowest-order surface mode in our layered medium was calculated using a recently developed formalism.[1] We note that the relatively "slow" intensity decay is due to the fact that the transverse propagation constants are real in both layers (the solutions are sinusoidal everywhere), i.e., the longitudinal propagation constant β satisfies $(\omega/c)n_2 > \beta < (\omega/c)n_1$, where n_1 and n_2 are the layer indices of refraction (see Fig. 2).

The measured surface wave intensity distribution is shown in Fig. 3. This plot was obtained by focusing the output of a 1.15-μm He-Ne laser on the cleaved edge of the sample and by scanning the magnified (×43) image of the output edge[5,6] past a narrow slit and detection combination. The resulting intensity distribution is shown in Fig. 3. The peaks in the Bloch tail are separated by a distance of 0.5 μm, which is beyond the resolution limit of our optical setup. However, the Bloch decay envelope of the transverse intensity distribution as measured from our experiment is consistent with our theoretical calculation (Fig. 3).

FIG. 3. Measured transverse intensity distribution of the surface wave.

All the theoretical discussions to date[1] have dealt with ideal periodic layers. The layered structures grown by MBE possess a high degree of periodicity and are well described by such a theory. The thickness control in the LPE-grown layers, however, is inferior to that of the MBE and the fractional rms thickness variation in our structure was measured at ~10%. It was somewhat surprising that all our grown layers exhibited clearly the existence of well-confined surface modes. A calculation of the modes of a 10-layer medium was carried out for random thickness layers with the rms thickness deviation as a parameter. The calculations used the matrix approach of Ref. 1. It was found that distinct surface modes persist up to a fractional rms thickness deviation of $\sigma = 20\%$. An example of a computed field distribution calculation of a structure with $\sigma = 20\%$ is shown in Fig. 4.

In conclusion, we have studied and demonstrated surface wave guiding in multilayer stacks grown by liquid phase epitaxy. The possibility of making multilayer stacks with Bragg reflection properties by liquid phase epitaxy has potential importance in applications such as optical filters for wavelengths in the infrared. Our experiments, as well as numerical calculations, indicate the persistence of surface modes and energy gaps, even in media with large deviations from perfect periodicity.

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