amplitude of the transmitted pulse was proportional to the conductivity of the sample and was measured by determining the change in the optical sampling beam polarisation due to a linear electro-optic effect in the cell. The intrinsic time resolution of this experiment is defined by the laser pulse duration. It was however a little worse than 7 ps because of the poor impedance matching at the place where the sample was connected into the stripline structure.

The investigated samples were prepared from δ-doped GaAs epitaxial layers as grown by metalorganic chemical vapour deposition on semi-insulating GaAs substrates. Trimethylgalliumetherate and 5% arsine in hydrogen were used as Ga and As sources and the dopant source was 0·024% silane in argon. Two δ-layers, separated by 0·05 μm thick undoped GaAs layer, were grown. The spike doping was achieved by interrupting the growth of undoped layer, purging the reactor with hydrogen, then introducing silane into the reactor for a short time, purging the reactor again, and resuming the growth. The concentrations of 2D electrons in δ-layers from $8 \times 10^{11}\,\text{cm}^{-2}$ to $2 \times 10^{12}\,\text{cm}^{-2}$ were measured by the Hall-effect technique. Their distribution across the thickness of an epitaxial layer was determined by the C/V method on a layer with a single δ-doped region which was grown at the same conditions. The profile widths of ~ 10 nm were obtained. The measured low-field Hall mobilities were $2\text{–}2{\cdot}5 \times 10^3\,\text{cm}^2/\text{V s}$ at 300 K. All measurements were performed at room temperature.

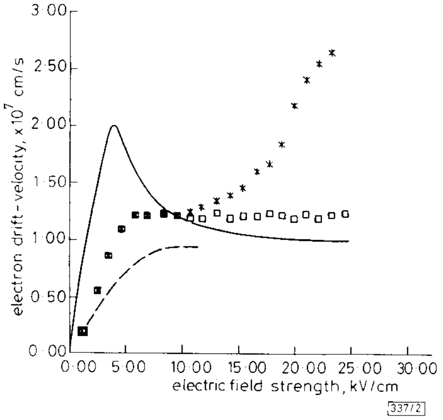

Fig. 2 *Drift velocity dependencies on electric field strength*

- - - - heavily doped GaAs
——— theory for pure GaAs
□ experimental j/en_s values for δ-doped layer with pulse duration = 30 ps
∗ experimental j/en_s values for δ-doped layer with pulse duration = 300 ps

Experimental dependencies are presented in Fig. 2. The first one (open squares) was measured at 30 ps from the electric pulse beginning. Because this value is shorter than the electron transit across the sample time, the electric field distribution in the sample remains homogeneous during the measurement and the electron drift velocity can be evaluated simply as

$$v_d = I/en_s d$$

where I is the current, e is the electron charge, and d is the width of the sample. This experiment shows that the electron drift velocity in δ-doped GaAs saturates in the high-field range at the value of approximately $1{\cdot}2 \times 10^7$ cm/s.

The current/voltage characteristic measured at 300 ps from the high-field pulse beginning is similar to the short pulse measurement only for the fields lower than 10 kV/cm. At the higher electric fields a time-dependent increase in current is observed. The reason for that increase is not well understood yet. It can be either due to the field redistribution and avalanche break-down in the high-field domain or due to the minority carrier injection. Clearly, the use of short pulses is essential in order to eliminate those undesirable effects.

Velocity-field characteristics for pure n-type GaAs[7] and highly doped ($n = 2 \times 10^{18}\,\text{cm}^{-3}$) GaAs epitaxial layers[5] are plotted in Fig. 2 for comparison. The common feature of both homogeneously and δ-doped layers is the absence of the negative differential mobility region on $v_d(E)$ dependencies. It seems reasonable to explain the disappearance of this effect for the same reasons; the ionised-impurity scattering effect and the reduction of the effective intervalley $\Gamma - L$ separation in the conduction band. The latter effect is due to the rise of Fermi level with doping, which is of the order of 80 meV in both cases. Therefore electrons are populating the subsidiary L minima even at low electric fields and the negative differential maturity region disappears.

Most interesting is, however, the comparison between the saturated velocity values for various samples. The electron drift velocity in δ-doped GaAs exceeds substantially its value in pure GaAs. Clearly, it would not be correct to draw some definite conclusions on the basis of comparison between the results obtained in various works by different techniques. Nevertheless, we can argue that the doping of 2-DEG channel, as in δ-doped layers, does not lead to a decrease of saturation velocity. It seems therefore that 2-DEG structures with doped channels are also attractive for high-frequency applications.

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SELECTIVE AREA EPITAXY AND GROWTH OVER PATTERNED SUBSTRATES BY CHEMICAL BEAM EPITAXY

Indexing terms: Epitaxy and epitaxial growth, Semiconductor lasers

Selective area epitaxy and growth over patterned substrate using chemical beam epitaxy (CBE) were investigated. Truly selective area epitaxy with no deposition over the SiO_2 masks has been routinely obtained with excellent epilayer morphology. Uniform coverage was obtained for regrowth over etched mesas to form buried heterostructures. For growth over etched channels, very unique growth characteristics were obtained. Buried crescent stripes similar to those formed by liquid-phase epitaxy inside channels were also obtained by CBE. These growth characteristics demonstrated the unique capabilities of CBE.

Chemical beam epitaxy (CBE)[1] has been employed to prepare both low threshold GaInAsP/InP bulk-active-layer[2,3] and GaInAs/GaInAsP multi-quantum well (MQW) lasers.[4,5] In these lasers, the regrowth to form the buried heterostructure (BH) was performed by either metalorganic vapour phase epitaxy (MO-VPE) or liquid phase epitaxy (LPE). Recently, Tsang *et al.*[6] also demonstrated that high resistive Fe-doped InP can be grown by CBE. In this letter, we present some initial results on the studies of selective area growth and growth over patterned substrates by CBE. Though such growths are important for current injection laser formation and optoelectronic integrated circuits, very few studies have been reported thus far.[7,8]

The growth experiments were performed in a modified Riber CBE 32 with rotation during growth. Heterostructures of GaInAs/InP and GaInAsP/InP were grown using triethylgallium (TEGa), trimethylindium (TMIn), arsine AsH_3 and phosphine, PH_3. Fig. 1 shows the surface morphology of as-grown GaInAs/InP superlattice over SiO_2 mask patterns under phase contrast microscope at low and high magnifications. It is seen that there was absolutely no deposition over the SiO_2 masks (the dark patterns) and the superlattice grown has excellent morphology (the area in between the masks). A scanning electron micrograph (SEM) of the cross-section is shown in Fig. 2. The use of superlattice (two periods) helps to delineate the time evolution of the growth along the mask edge. By etching down into the substrate, planar selective growth can be achieved. This may be important for fine-line lithography. In the above sample, the growth temperature was 545°C. Such clean selective area epitaxy is a unique feature of CBE not present in molecular beam epitaxy MBE (including gas-source MBE) and atmospheric MO-VPE.

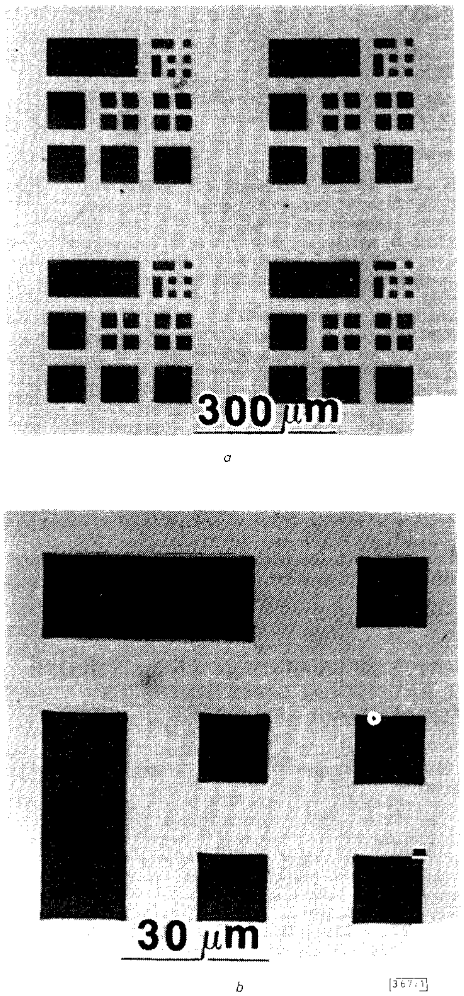

Fig. 1 *As-grown surface morphology taken under phase contrast microscope of selective area epitaxy of GaInAs/InP superlattice (2 periods) over SiO_2 masks (dark patterns)*

The multilayers are the in-between areas. No deposition was observed over the SiO_2 masks

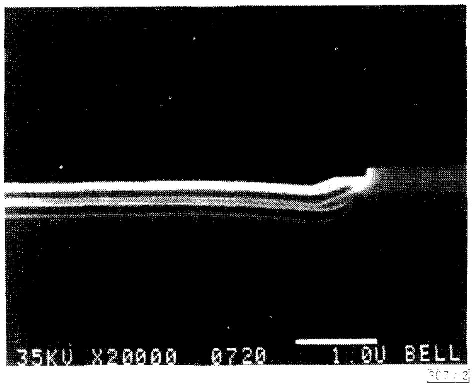

Fig. 2 *SEM photograph showing the cross-section of the selective area growth*

In this example, the substrate was etched down to achieve planarity

To investigate the possibility of forming BH lasers, we also studied the growth characteristics by CBE over patterned substrate Fig. 3 shows an SEM photograph of the cross-section of a BH laser structure. The active mesa is ~1·5 μm wide. The regrown multilayer structure consists of 1·45 μm InP, 0·13 μm GaInAs and 0·2 μm InP. Excellent and uniform coverage over the mesa was obtained.

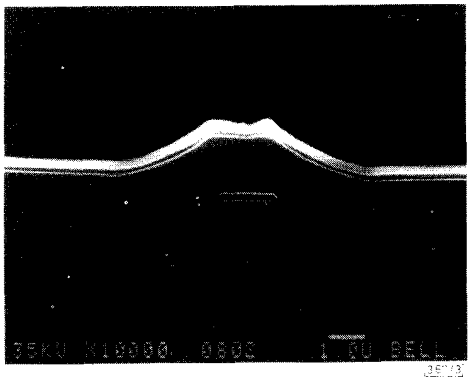

Fig. 3 *SEM photograph showing the cross-section of regrowth over an etched mesa*

Very unique growth characteristics were obtained by CBE over channels etched into the substrate as shown in Fig. 4. In this example, an InP/GaInAsP/InP/GaInAsP (etched away during the staining process for layer delineation) multilayer structure was grown over V-grooves etched into the substrate. Interestingly, the growth characteristic inside the V-groove is very similar to those grown by LPE.[9,10] Curved and completely buried crescent active stripes were formed. Again, this is completely different from those grown by MBE in which the layers very much conform to the shape of the etched pattern.[11] Such growth characteristics point to the possibility of forming buried crescent heterostructure lasers by CBE employing a single epitaxial growth. Such experiments are presently under investigation.

In summary, we have investigated selective area epitaxy and growth over patterned substrate by CBE. We observed that true selective area epitaxy can be routinely achieved with excellent morphology. Uniform coverage was obtained for regrowth over etched mesas. For growth over etched channels, very unique growth characteristics were obtained. Buried crescent stripes similar to those formed by LPE were also obtained by CBE. These growth characteristics further demonstrate the unique capabilities of CBE.

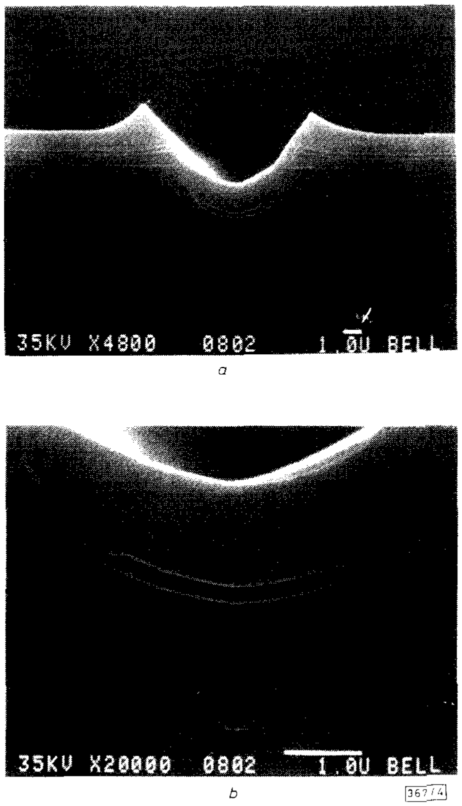

Fig. 4

a SEM photograph showing the growth of a buried crescent InP/GaInAsP/InP multilayer structure over a V-groove by CBE
b A magnified view of the buried crescent structure

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REDUCTION OF SURFACE WAVES IN CHIROSTRIP ANTENNAS

Indexing terms: Microstrip, Antennas

The quantitative study of surface wave propagation in a new class of printed-circuit antennas named *chirostrip** antennas† is given. It is shown that by using lossless chiral materials as substrates of such antennas, surface wave power can be significantly reduced. This design will provide a promising solution for highly efficient, wideband printed-circuit antennas.

In recent years, integrated-printed-circuit antenna technology has proven to be a logical means of building very thin planar, low profile antenna structures. Clearly there are numerous advantages associated with such antennas. Low profile, light weight, compatibility with monolithic integrated circuits, ability to be made conformal and easily mounted on airborne platforms, low cost and integrability with other units such as signal processing circuits are among the favourable features of microstrip antennas.[1] However, it should also be mentioned that some constraints exist in their design such as energy loss in dielectric layers, ohmic loss in thin metallic surfaces, extraneous radiation from feeds and junctions, and perhaps more importantly, generation of surface waves in dielectric substrates and/or superstrates. Excitation of surface waves, which propagate along and hug dielectric coated surfaces in microstrip antennas, generally degrades the radiation efficiency and sidelobe level of these devices. This is because a fraction of the total energy goes into the substrates and/or superstrates as surface waves and eventually radiates from the boundaries of the antenna structure. In addition, surface waves are among the major mechanisms responsible for mutual coupling and crosstalk among antenna elements and arrays. For microstrip antennas, the efficiency, sidelobe level and bandwidth are, in general, affected by the reduction in the thickness of substrates. A vast amount of research, both theoretical and experimental, has been directed towards investigating ways of improving efficiency, bandwidth and sidelobe level control of microstrip antennas without sacrificing the cost and operational advantages. There have been many successful ideas to develop new methods and designs, and to use new materials with low loss and complex properties to reduce the surface wave propagation in antenna layers. One such idea is the use of chiral materials as substrate and superstates in printed-circuit antennas. This idea was first introduced by Engheta,[2] and the name *chirostrip* was coined then. It was predicted that, due to the unconventional polarisation properties of waves in chiral media, the surface wave power would generally be reduced if a chiral layer were used as a substrate. We present the results of our quantitative analysis on surface

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* Registered trademark
† Patent pending