References

FABRICATION OF DOMAIN REVERSED GRATINGS FOR SHG IN LNBO, BY ELECTRON BEAM BOMBARDMENT

Inducing terms: Lasers and laser applications, Crystals, Electron beam lithography

A novel technique for the lithographic definition and the fabrication of domain reversed regions in LNBO, is reported, with application to periodic structures for SHG. For the first time, to our knowledge, domain reversal has been achieved on the negative c-face of the crystal. Such a structure should be useful for quasi-phase-matched second harmonic generation of infra-red laser radiation.

Introduction: Second harmonic generation (SHG) of infra-red radiation in lithium niobate (LNBO) optical waveguides has been the subject of much research. Many nonlinear optical devices have been demonstrated using a variety of phaseshifting techniques including birefringence, modal dispersion, and Cerenkov radiation. An alternative method, known as quasi-phase-matching, has been demonstrated recently for SHG in integrated optical waveguiding structures. Quasi-phase-matched SHG is best achieved by periodic reversal of the sign of the nonlinear coefficient  of the material and is, potentially, a very efficient method of achieving SHG. By appropriate choice of the period of the modulation, it is possible to phase-match for any arbitrary fundamental wavelength.

It is known that titanium indiffusion at temperatures near the Curie temperature of congruent LiNbO (1140°C) can result in domain reversal on the positive c-face of LNBO, but not on the negative c-face. Outdiffusion of Li,O can also lead to domain reversal on the positive c-face. Both of these techniques have been used to produce periodic domain reversed gratings for quasi-phase-matched SHG. It is, however, often the negative c-face which is preferred for waveguide fabrication. We report here, for the first time, periodic domain reversal on the negative c-face, which has been achieved by electron beam bombardment of the negative c-face at temperatures well below the Curie temperature. To realise the periodic structure it is necessary to use a periodic metallic mask to prevent the penetration of the electron beam into the crystal. This paper will report on the design and fabrication of such a mask and also on the technique for subsequent formation of a periodic domain reversed structure on the negative c-face of the crystal. This technique leads to a domain reversed grating, but avoids completely the titanium indiffusion or high temperature outdiffusion requirements of the other techniques.

Grating fabrication: There are three requirements that must be satisfied so that a domain reversed grating can be fabricated by electron beam bombardment and exploited successfully for SHG. These requirements are: the correct periodicity in the first order grating to compensate for the phase mismatch between the fundamental and the harmonic waves, a masking layer that can absorb the electrons efficiently in the regions where domain reversal is not desired and, finally, it must be possible to provide an electrical contact to the grating so that a poling field can be applied to the crystal. A schematic diagram of the required grating structure is shown in Fig. 1.

![Fig. 1 Arrangement for domain reversal by electron beam bombardment](https://example.com/fig1)

The period required for a first order grating to obtain quasi-phase-matched SHG of 1.06 µm laser radiation was experimentally estimated to be 3-4 µm for a z-cut proton exchanged waveguide with a waveguide depth chosen to optimise the conversion efficiency for SHG.

Gold was chosen for the mask since it is an efficient absorber of electrons and is compatible with standard photolithographic techniques. Using a Monte Carlo simulation of the Bethe relation, the depth of penetration of electrons in both LNBO and gold was calculated as a function of the incident electron energy. The Bethe relation is only strictly valid for electron ranges calculated in single elements. In the Bethe model, the penetration depth is dependent on the atomic number and the mass number of the element and also on the ionisation potential of the element. To calculate the electron range in the LNBO, the compound was treated as a single element, with the atomic number, the mass number and the ionisation potential being approximated by calculating a weighted average for each using the appropriate values of atomic numbers and atomic weights, oxygen and niobium respectively. Fig. 2 shows a graph of penetration depth as a function of incident electron energy. This calculation does not take account of the temperature of the substrate and it would be expected that, at the temperatures to be used for domain reversal, the electron energies required will be greater than those indicated by our analysis, due to increased scattering. The penetration depth of 1 µm in the LNBO was chosen to be greater than the depth of the waveguide to be...
used (approximately 0.7 μm). The gold film thickness required
was then on the order of 0.4 μm. To provide electrical contact
to the entire surface region undergoing bombardment and
also to promote adhesion of the gold film, a 50 nm film of
nickel was deposited onto the crystal prior to the deposi-
tion of the gold. Deposition of both films was by thermal
evaporation. Electrical contact to the rear face was provided
by a 50 nm film of nickel and 0.2 μm of gold, again depos-
ited by thermal evaporation. After photolithography, the gold
was etched in a 1:1 mixture of deionised water and a saturated
solution of potassium iodide in iodine, an etchant that did
not attack the nickel layer.

Domain reversal. Domain reversal by electron beam bombard-
ment of bulk LiNbO₃ has been demonstrated previously using
the technique just described. The mechanism for domain
reversal can be understood as follows. By exposing an
LiNbO₃ crystal to a beam of electrons, a transient vacancy
can be generated in the oxygen triangles of the crystal struc-
ture as the electronic excitation favours the formation of a
transient molecular oxygen ion state. A poling field is applied
to the crystal along the c-axis, as in conventional poling,
causing the temporarily disordered lithium ions to move into
an ordered (i.e. poled) structure. Fig. 1 shows the required
direction of the poling field required to generate periodic
domain reversal on the negative c-face of the LiNbO₃.
The domain reversal was carried out at a substrate tem-
perature of approximately 580°C under an applied poling field
of 10 V cm⁻¹. The sample was exposed to an electron beam of
spot size 9 μm for a period of 1 hour, with a total dose of
approximately 1.7 × 10¹⁹ electrons at 10 keV. The electron beam
current was 8 μA. At temperatures of 580°C under vacuum,
the LiNbO₃ surface was partially reduced and, consequently,
after domain reversal, the sample was annealed in air for 5
hours at 650°C to replace the lost oxygen. The domain
reversed regions of the LiNbO₃ were then revealed by etching
in a 1:2 mixture of hydrofluoric and nitric acids. This etchant
attacks the negative c-face only while the positive c-face
remains unetched. Domain reversed regions were therefore
shown up due to the difference in the etch rates. Fig. 3 shows
a scanning electron micrograph of part of the grating struc-
ture after etching, with the domain reversed regions clearly
visible. Generally similar features have also been observed
optically.

Work is currently underway to demonstrate SHG in proton
exchanged waveguides fabricated in a LiNbO₃ substrate with
a periodically domain reversed grating structure realised by
the technique described here.

Conclusions. For the first time, to our knowledge, first-order
periodic domain reversal for quasiphase-matched SHG has
been demonstrated on the negative c-face of an LiNbO₃
crystal. The domain reversal was achieved by selective elec-
tron beam bombardment of the LiNbO₃. This technique
should also be useful for quasiphase-matched SHG in other
ferroelectric crystals that cannot be conventionally phase-
matched, for example lithium tantalate.

Fig. 2 Domain reversed grating revealed by chemical etching

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SUBMICRON-GATE ION-IMPLANTED InGaAs/As/GaAs MESFETS WITH GRADED INDIUM COMPOSITION

Inducing terms: Semiconductor devices and materials, Indium comounds, Gallium arsenide, Field effect devices

0.25 μm and 0.5 μm gate ion-implanted MESFETS have been fabricated on InGaAs/GaAs epitaxial layers. These layers are grown by MOCVD on three inch diameter GaAs substrates with the indium mole fraction graded from 15% at the InGaAs/GaAs heterointerface to 0% at the surface. Both devices have excellent DC and microwave performance. From S-parameter measurements, extrinsic current gain cutoff frequencies fT of 130 and 61 GHz are obtained for the 0.25 and 0.5 μm gate MESFETs, respectively. This work investigates the potential of small-bandgap InGaAs materials for submicron-gate MESFET applications.

Recently, there has been growing interest in InGaAs materials for high performance FET devices. Compared with AlGaAs/GaAs HEMTs, enhanced microwave performance and current density have been demonstrated with AlGaAs/InGaAs pseudomorphic HEMTs due to higher electron velocity and larger conduction-band discontinuity. Owing to the difficulty in forming a good Schottky contact, InGaAs is chiefly used as the channel material for heterojunction devices, such as HEMTs and MISFETs, whose device structures have a layer of large bandgap material in between the Schottky gate and the active channel. We have fabricated 0.5 μm gate MESFETs with the Schottky gate directly deposited on a graded InGaAs channel. This InGaAs MESFET shows improved Schottky gate characteristics.

In this letter we report that excellent device performance comparable to the best reported results from AlGaAs/InGaAs HEMTs and MISFETs can be achieved with submicron-gate ion-implanted InGaAs MESFETS. The state-of-the-art results provided by the InGaAs MESFETS demonstrate the high potential of InGaAs materials for MISFET applications. The InGaAs layer is directly grown on three inch diameter GaAs substrates by using an EMCORE GS3300 MOCVD reactor without growing any kind of buffer structures. The active layer structure consists of 160 Å of In0.05Ga0.95As layer with the InAs fraction graded from 15% at the InGaAs/GaAs heterointerface to 0% at the wafer surface. The graded InAs composition contributes to better Schottky contact. Photovoltage spectroscopy is used to calibrate the InAs concentration. The growth rate for these InGaAs layers is typically 2 μm/hr depending on the indium fraction. The source materials for MOCVD growth are arsine, trimethylgallium and ethylidyldimethylindium. After MOCVD growth, silicon ion implantation is used to dope the InGaAs layers to a peak carrier concentration of 1 to 2 x 10^18 cm^-2.

Standard MESFET processing techniques are used to fabricate 0.5 μm and 0.25 μm recessed gate devices. The drain-to-source spacing is 2 μm with a gate-to-source spacing of 0.25 μm to reduce the source resistance. Device isolation is achieved by mesa etching. The source and drain regions are defined by optical lithography, followed by AuGeNi/Au metal evaporation and ohmic alloying. The 0.5 μm and 0.25 μm gates are defined by deep UV photolithography and electron beam lithography, respectively, and completed by Ti/Pt/Au gate metallisation on the recessed channel.

Based on Matthews and Blakeslee’s model, the critical thickness for a thin InGaAs layer on GaAs substrates is around 200 Å. Beyond the critical thickness, misfit dislocations are generated to accommodate lattice mismatch. The total thickness of the InGaAs layer in our structure is 1600 Å. Although the InAs fraction is graded through the active layer, the device channel has high defect density, as revealed by the cross hatch patterns all over the wafer surface. Similarly to the previous results, DC characteristics of these InGaAs MESFETS behave normally with a pinchoff voltage of ~ 2V. Both 0.5 μm and 0.25 μm gate devices have a gate-to-drain breakdown voltage of around 5 V. In this letter, we will emphasis below the performance improvement as the gate length is reduced from 0.5 to 0.25 μm.

Biased at Ids (zero gate voltage), the 0.5 μm gate device has an extrinsic transconductance (gm) of 300 mS/mm at a current density of 440 mA/mm. When the gate length is reduced to 0.25 μm, the InGaAs MESFET shows an Imax of 490 mA/mm with a corresponding gmax of 444 mS/mm. The difference in the Imax is mainly due to variation of the gate recess depth. The gmax of the InGaAs MESFET is therefore improved by 50% when 0.25 μm gates are used. Since output conductance (gds) has a high frequency dispersion effect, the DC output conductance and consequently the voltage gain (gmax/gds) are not meaningful figures of merit for microwave FETs. As a result, we rely solely on S-parameter measurements and make direct comparison of microwave gains for 0.5 μm and 0.25 μm gate devices. The DC results are summarised in Table 1.

<table>
<thead>
<tr>
<th>Gate length</th>
<th>0.5 μm</th>
<th>0.25 μm</th>
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<tbody>
<tr>
<td>gm at Ids</td>
<td>300 mS/mm</td>
<td>444 mS/mm</td>
</tr>
<tr>
<td>lmax</td>
<td>440 mA/mm</td>
<td>490 mA/mm</td>
</tr>
<tr>
<td>fT</td>
<td>61 GHz</td>
<td>120 GHz</td>
</tr>
<tr>
<td>MSG—12 GHz</td>
<td>14.2 dB</td>
<td>17.3 dB</td>
</tr>
<tr>
<td>—18 GHz</td>
<td>12.4 dB</td>
<td>15.0 dB</td>
</tr>
<tr>
<td>—25 GHz</td>
<td>11.4 dB</td>
<td>14.1 dB</td>
</tr>
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</table>

Microwave S-parameters are measured from 0.5 to 25 GHz by using an HP8510 automatic network analyser and Cascade Microtech microwave probes. The microwave probes are calibrated using the impedance standard substrate (ISS) from Cascade Microtech and the open condition required to calibrate the system is set by lifting the probes in the air. This calibration procedure ensures the measured fT is accurate and extrinsic without any subtraction of parasitic capacitance.

Using a 100 μm gate width device, the S-parameters for the 0.5 μm gate InGaAs MESFET are measured at lsat (zero gate voltage) and a drain voltage of 1.5 V. The current gain (H11) and the maximum stable gain (MSG) as a function of frequency are obtained and shown in Fig. 1. The extrapolation of

![Fig. 1 Current gain (H11) and maximum stable gain (MSG) as a function of frequency for the 0.5 μm gate InGaAs MESFET fT = 61 GHz](image-url)