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Advanced Laser Gratings: Fabrication and Assessment in the Production Environment

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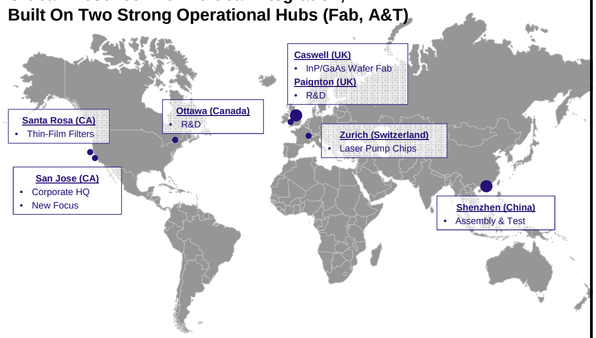
Advanced Laser Gratings: Fabrication and Assessment in the Production Environment

- Introduction
- Laser Gratings – what, why, where
- Key process parameters
- Holographic and e-beam grating exposure
- Grating etch processes
- Grating Assessment
- Summary

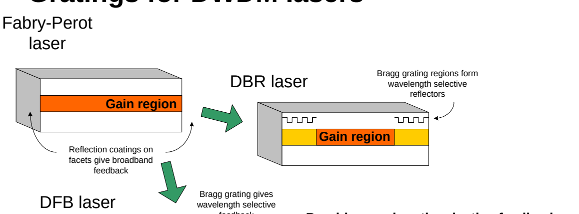
Global Presence With Vertical Integration, Built On Two Strong Operational Hubs (Fab, A&T)

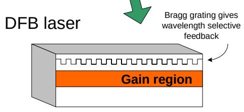


Caswell InP Wafer Fab

- 57k sq.ft. (5,300 m2) clean room
- 3” processing – increased throughput, high yields, high process reliability
- Equipment capacity >500 3” InP wafers/month
- Rebuild value >$500M

Gratings for DWDM lasers





- Provide wavelength selective feedback
- Reduce linewidth – single longitudinal mode
- DFB – grating continuous through gain section
- DBR – gratings outside gain section acts like a FP laser with wavelength selective mirrors

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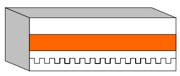
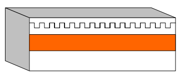
Location of grating structures in laser

- ‘Gratings down’ – gratings below the active region
  - subsequent growth must match the grating wavelength….

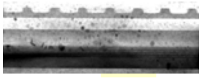


- ‘Gratings up’ – grating in or above active region
  - grating wavelength can be tailored to match growth

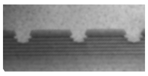


Types of laser grating

- Index coupled
  - periodic variation in the laser mode index along the cavity



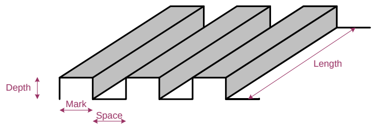
- Gain coupled
  - grating structure gives rise to periodic variation in gain along the cavity



Key grating parameters – device design

- Pitch
  Corresponds to half the wavelength of the light in the laser cavity
  - for laser wavelengths in the range 1300nm to 1600nm the pitch varies from around 200nm to 250nm
- Coupling strength (Kappa)
  Depends on
  - grating shape (mark space ratio, depth, profile)
  - mode overlap (growth, ridge etch)

Process scales and tolerances



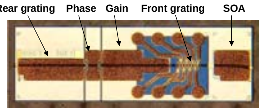
- Feature size – 50-150nm wide, 30-90nm deep, from 30µm up to 65mm long
- Mark space ratio tolerance, 1+/- 0.3
  corresponds to 120nm +/- 16nm @240nm
- Depth tolerances +/- 3 to 7nm
- Pitch tolerance +/-0.05nm (+/-0.02%)
- Cleanliness – gratings sit at a growth interface within the mode, loss issues, failure issue (particularly gain coupled lasers where interface is within the gain region)

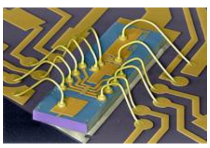
Periodic structures

- Laser responds to periodic nature of grating structure
  - laser mode 'sees' between 1000 – 4000 grating periods
  - mode width typically a few µm
  - reasonably tolerant of occasional, *non-periodic*, flaws (however, these can give rise to increased scatter loss and degrade device performance)

Advanced gratings – DS-DBR Tuneable Laser

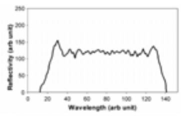
- DBR structure: separate front and rear gratings
- Front grating: wideband switchable reflector
  - provides coarse tuning
- Rear grating: multi-wavelength reflector with seven separate reflection peaks
  - provides fine tuning
- Total tuning range in excess of 45nm

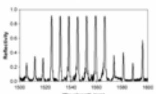


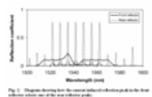


Gratings for DS-DBR tuneable laser

- Front grating comprises highly 'chirped' grating – pitch changes rapidly along length of grating (~15nm over 300µm)
  - need continuous variation of grating pitch without phase steps
- Rear grating comprises seven evenly spaced peaks
  - need to control peak height
- Both gratings produced in single etch stage – same grating depth for front and rear gratings







Grating Fabrication – Process Summary

All start as surface relief gratings. Previous and subsequent growths determine final grating type

- Wafer clean
- Resist coat
- Grating exposure/write (holographic or e-beam)
- Develop
- *Assessment*
- Etch (wet etch or RIE)
- *Assessment*

Process control

Single fab used for both production and development

- Production requirements
  - Uniformity over wafer: high chip yield
  - Wafer to wafer repeatability: high wafer yield
  - Need to know yield achieved at this stage in the process
    - process costs increase with stages complete (edge emitting devices – no on-wafer testing)
- Development requirements
  - Known grating parameters
    - effective feedback on device design performance

- GRATING PROCESS ASSESSMENT KEY TO HIGH PRODUCTION YIELDS AND EFFECTIVE DEVICE DEVELOPMENT

Resist coatings

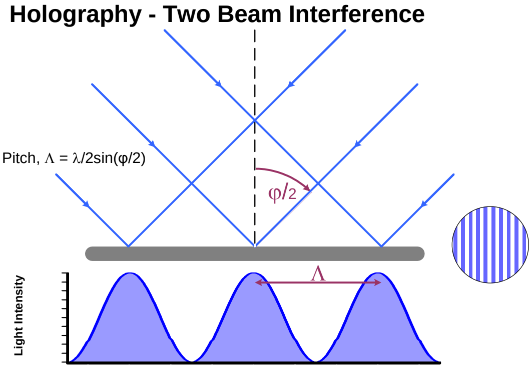
- Holographic exposures
  - Positive photoresist
  - thin resist to avoid standing wave patterns
  - thickness control better than ±3%

- E-beam exposures
  - e-beam resist
  - thin resist for fine feature sizes
  - thickness control to better than ±8%

- Automated resist coating increases repeatability
- Good wafer surface quality required
  - Growth defects can disrupt resist thickness over much larger area of wafer than defect dimensions

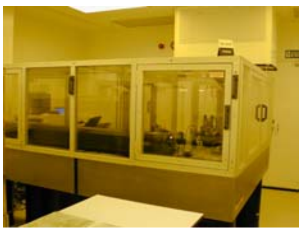
Holography - Two Beam Interference

- Pitch, $\Lambda = \lambda/2\sin(\varphi/2)$

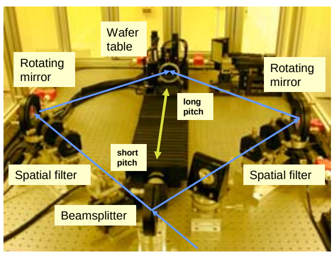


Holographic exposure kit

- In-house designed and built
- 351nm wavelength
- Large area gratings up to 3inch wafers
- Automated beam alignment
- Automatic pitch adjustment 190 to 260nm
- Automatic pitch setting
- Alignment to major flat to ±0.1degrees
- Exposure time approx. 10s
- Cycle time 6-8 minutes per wafer



Holographic grating kit kite



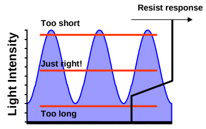
Wafer table moves up and down and mirrors rotate to adjust grating pitch

Holographic Grating Fabrication - Process Control

- Pitch tolerance +/-0.05nm (+/-0.02%)
- Achievable as grating pitch set in Fourier space by:
  - Laser wavelength: Argon ion laser, 351.10 +/-0.01nm
  - Equipment geometry: angle tolerance +/-0.005 degrees

Holographic grating exposures

- 'Analog' exposure cf. 'digital' exposure with mask
- Interference pattern produces a sinusoidally varying exposure intensity
- Residual light in minima (fringe visibility)
- Exposure time critical
  - too short and spaces won't clear
  - too long and marks will disappear
  - tolerance ~ ±0.2s (~ ± 2%)
- Requires
  - tight control of resist thickness
  - stable laser intensity
- Control achieved by use of exposure calibration wafers (multiple exposures, range of exposure times)



E-beam grating exposure

- Direct write process
- Grating spaces are written line by line
- Only writes grating where required
- Used for specialised grating structures for DS-DBR
  - High chirp front grating
  - multi-wavelength rear grating
- Exposure dependent mark space ratio
  - as with holography use 'banded' dose test wafers to improved process control

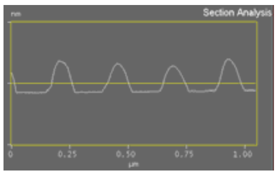
Assessment of resist pattern

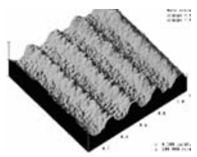
- Key point to assess wafers
  - Out of spec wafers can be reworked
- Need to measure 'footprint' of resist pattern, as this is transferred into semiconductor during etch
- Diffraction efficiency scanning not effective technique as resist is partially transparent to assessment wavelength
  - forms a phase grating
  - very sensitive to volume of resist (varies with exposure time, fringe visibility, development)
  - not very sensitive to resist footprint
- AFM scanning very effective imaging tool
  - although only small area measured

AFM Assessment

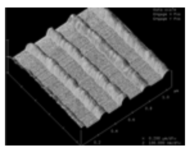
- Autoloading
- Auto scanning for rapid batch assessment

AFM assessment - Holographic resist grating



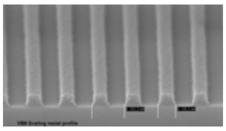


- AFM used to determine resist grating mark space ratio prior to etch
- Target mark/space is 1±0.3



E-beam resist grating

- AFM used to assess mark space ratio prior to etch
- Target mark/space is 1±0.3



Comparison of Holographic and E-beam exposure techniques

Holography

+ Large grating area (DFB)
+ Faster wafer write time
+ Pitch and chirp settable at point of exposure
+ inherent grating apodisation
- Limited flexibility in grating type
- Masking required on wafer to define grating areas for DBR

- Fixed requirements
- Large wafer volumes
- Wafer to wafer pitch adjustment

E-beam

+ Maximum flexibility of grating design (multiwavelength reflectors, high chirp rate, phase shifted gratings)
+ Grating only where required (no masking required)
+ Many grating types on a single wafer
- Slower wafer write time

- Specialised grating designs (DS-DBR)
- Rapid prototyping

Grating Etch Processes

Wet Etch

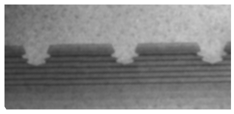
- Multistage, manual process
- Uses 'sacrifical' epi layers to minimise organic contamination at grating interface
- Triangular/trapezoidal profiles as use crystallographic etches

Dry Etch

- Single stage CH_4/H_2 RIE
- Rectangular profile

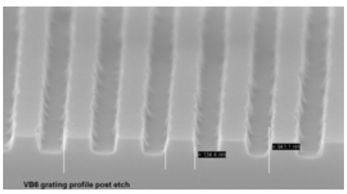
Wet etch grating

- Depth control via time, temperature



Dry Etch Process

- Low power CH_4/H_2 RIE
- Unidirectional etch
- Produces rectangular profile
- Depth control by etch time

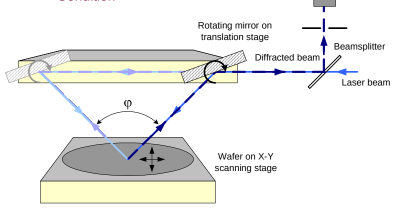


Grating Assessment

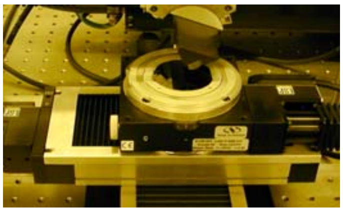
- Non destructive assessment technique
- Measures pitch, diffraction efficiency
- Calibrated against SEM/TEM images on test wafers to give mark-space and depth.

Littrow Condition

$\Lambda=\lambda/2\sin(\varphi/2)$



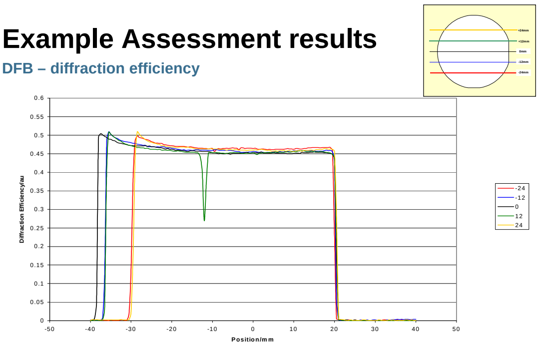
Grating Assessment Kit



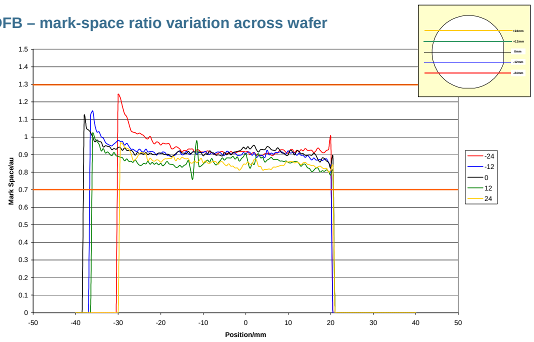
- In house designed and built
- Automatic beam location and wafer alignment
- Variable resolution (DFB/DS-DBR)
- Variable scan size (2inch and 3inch wafers)
- Custom scans

Example Assessment results

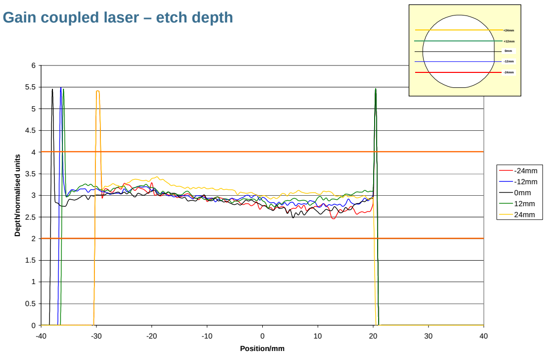
DFB – diffraction efficiency



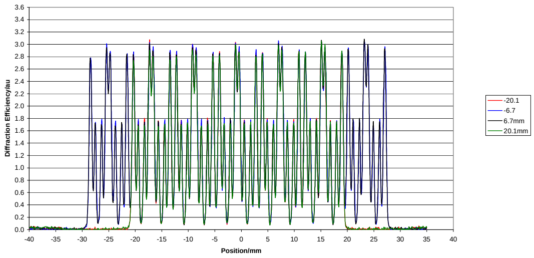
DFB – mark-space ratio variation across wafer



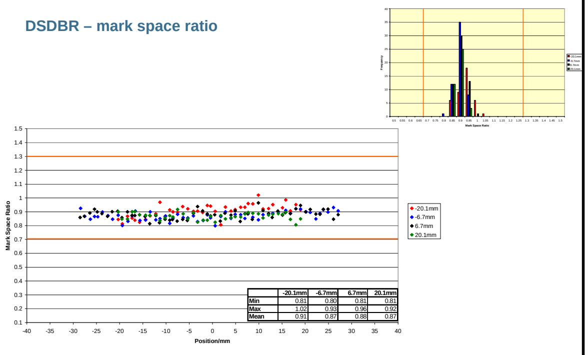
Gain coupled laser – etch depth



DS-DBR – diffraction efficiency



DSDBR – mark space ratio



	-20.1mm	-6.7mm	6.7mm	20.1mm
Min	0.81	0.80	0.81	0.81
Max	1.02	0.93	0.96	0.92
Mean	0.91	0.87	0.88	0.87

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Summary

- Laser grating fabrication requires nanometre process control
  - Periodic nature of structures gives rise to different control requirements from discrete nanostructures
- Holographic techniques give speed and continuous parameter control for fixed grating designs
- E-beam techniques give flexibility and adaptability for complex grating designs and rapid prototyping
- Non destructive assessment techniques (AFM, diffraction measurement) essential for tight process control and high yields
- Nanometre scale grating fabrication, using holography or e-beam exposure, is a practical production technique