A selection of research topics in semiconductor physics at the Cavendish Laboratories

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Outline of talk

• Split gate technology
• Surface Acoustic Wave driven devices
• Site control of quantum dots
• Ultra high resolution lithography
Split gate technology for 2D, 1D and 0D electronic devices

Two-dimensional electron gas (2DEG)

Material Growth by MBE

Growth Direction

- 10nm undoped GaAs cap
- 40nm doped AlGaAs
- 20nm undoped AlGaAs spacer
- 2DEG
- 1000nm undoped GaAs buffer
- GaAs substrate

Electron mobility $\mu$ (cm$^2$/V s)

Temperature $T$ (K)

Pfeiffer et al APL 55,1888 (1989)
Quantum wire
Quantized Conductance in 1D

- Making gate voltage more negative decreases well width and increases level spacing – depopulating energy levels one by one.

Number of occupied subbands


Quantum dot

source
drain
Examples of devices based on split gate technology
Quadruple quantum dot
Aharanov Bohm device with quantum dots
Making connections to isolated electrodes
Making connections to isolated electrodes
Surface Acoustic Wave Driven devices

1 μm transducer, used to create a mechanical surface acoustic wave (SAW) SAW speed is ~2800 m/s. GaAs is piezoelectric, so a travelling electric wave is created.

- SAW devices can be tuned to transport an integer number of electrons in each minimum, which leads to current quantisation.
- Metallic surface gates are used to define 1D channels. The spins of electrons in these channels can be used as qubits.
SAW driven single photon emitter
3GHz SAW transducer
3GHz SAW transducer
Quantum dots with non-invasive detectors
Dual channel SAW device for investigating electron interactions and entanglement
Magnetic gates 3nm Au + 20nm NiFe + 3nm Au
Spin Manipulation Using Nanomagnets

Nanomagnetic fingers designed to redirect an external field to a perpendicular direction have been fabricated.

The magnetic field in the gap has been imaged with electron holography. An external field of 1 T leads to ~190 mT in the gap.

It should therefore be possible to rotate injected electrons to \( \uparrow \).

Similarly designed nanomagnets can also be used to create an alternating magnetic field for use in ESR-type experiments.
InAs Quantum Dots for optical applications
Motivation

- Discrete density of states makes quantum dots ideal as single photon sources for quantum cryptography or optical quantum computation schemes.

Electrically Driven Single-Photon Source

P. Atkinson, Cambridge University, 2005
Stranski-Krastanov growth of InAs dots by MBE results in near-random dot distribution

1.2 \times 10^9 \text{ cm}^{-2}
2.55\text{ML at 0.01ML/s}
515^\circ\text{C}
P(A)=2.1\times10^{-7} \text{ mbar}
V/III flux \sim 450

P. Atkinson, Cambridge University, 2005
Site-control of dot nucleation

- Electron-beam lithography to pattern small holes (diameter ~60-140 nm)
- RIE etching (SiCl₄)/ wet etching (weak sulphuric acid based) to etch pits ~10-40nm deep
- Resist removal (solvent rinses, oxygen plasma ashing)
- In-situ low-temperature oxide removal by hydrogen plasma (preventing surface damage)

pre-growth after H plasma treatment

P. Atkinson, Cambridge University, 2005
Site-control of dot nucleation

P. Atkinson, Cambridge University, 2005
Site-control of dot nucleation

- Good single dot occupancy
- Dots on the verge of coalescing
- Some double dot occupancy
- Holes completely infilled
- No dots nucleating between patterns (less than the critical InAs thickness deposited)

P. Atkinson, Cambridge University, 2005
Photoluminescence

Observation of photoluminescence from nucleated dots

Data courtesy of Martin Ward, Toshiba Cambridge Research

P. Atkinson, Cambridge University, 2005
Nanoimprint masters for sub-10 nm patterning

Nanoimprint masters for sub-10 nm patterning

Acknowledgements

- Dave Anderson
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- John Griffiths
- Massaya Kataoka
- Dave Ritchie
- Saif Saifullah
- Martin Ward
Collaborative projects with KAIST

- **Towards 1nm lithography**
  Prof H S Kim (Sun Moon University) is developing optics for a low-voltage, high-resolution, e-beam micro lithography column. Dr D. G Hasko (Cavendish), has been collaborating by providing expertise for the resist processing which requires a deeper understanding to achieve nanometer scale resolution. One student has spent several weeks in Cambridge working on this project learning resist processing etc.
- Dr S B Lee (Hanyang University) is responsible for system integration of this tool and the Cavendish Lab has supplied hardware for the mechanics of some of this system.
• Dr G A C Jones who has a high-voltage electron beam lithography tool at the Cavendish Laboratory is collaborating with Dr S. B. Lee in an experimental program to create patterned templates to act as a seeding base for clusters of particles to be assembled out of solution. Arrays of etched pits of various shapes and sizes, of order a few 10s of nanometers have been fabricated on various substrates using the e-beam facility in Cambridge for Dr Lee to investigate cluster formation on these samples. (SBL)

• Mr Hongkee Yoon (KAIST student) spent ~8 weeks in the Cavendish working on a new project - 3 Dimensional, grey scale, e-beam lithography. (GACJ)

• Dr Jones has been working on other methods of achieving nanostructure fabrication in the “towards 1nm scale”. (GACJ)
3 dimensional, grey scale, electron-beam Lithography

Hongkee Yoon (Kaist)
Geb Jones (Cavendish)
David Anderson (Cavendish)
Motivation

• Applications in optical elements:
  • blazed gratings
  • sinusoidal, triangular gratings
  • zone plates
  • integrated surface lenses for optical interconnects
  • ……?

• Applications in circuit elements
  • air bridges
  • MEMs
  • ……?

• Suitable for mass replication using nanoimprint lithography
Dose vs resist thickness remaining

- Blue line is measured height (nm)
- Red line is calibrated height with max height set as 0
Monte Carlo simulation of 60keV e-beam exposure
1000nm A9 PMMA on Si (Z = 500nm)
1000nm A9 PMMA on Si (Z = 500nm)

Energy Density per Injected Electron
$E^*/(eV/um^3)$

Radius $R_i/um$
Proximity effects in e-beam exposure

For double Gaussian approximation to PSF, the energy deposited per electron (normalised to unity in the centre of a large area) is, \( E \sim \frac{g_{\alpha} + \eta g_{\beta}}{1 + \eta} \)
Dose pattern for 3Ghz SAW transducer
3D test pattern with 10 levels of height
Calculated dose pattern for 10 x 10 array of 5um square pillars having 10 levels of height.
Corner of 10 x 10 pillar array showing corrected doses calculated on 50nm grid
Exposed array without proximity correction
AFM image (uncorrected array)
AFM scan (uncorrected exposure)
Proximity corrected 10 by 10 array
AFM image (corrected exposure)
AFM scan (corrected exposure)
Sine wave grating slit pattern
Diffraction images from sine wave grating

slit diffraction images
“Towards 1nm lithography”

Sub-10nm, high aspect ratio patterning of ZnO nanostructures using zinc napthenate negative e-beam resist

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Why direct writing of oxides?

- Fundamental studies on nanoscale oxide systems
  - Basic transport properties, optoelectronics, nanophotonics, nanoferromagnetism, nanoferroelectricity, etc.

- To enable patterning of thick or complicated oxide layers
  - Conventional lift-off technique for patterning thick and complicated oxide layers does not work.
  - Use a spin-coatable oxide resist for direct writing to circumvent the problem associated with lift-off technique. It also improves tolerances and reduces processing steps.
Resist Preparation

Alkoxide Route (TiO₂, ZrO₂, Al₂O₃)

Naphthenate Route (ZnO)
Preparation of spin-coatable oxide resists of TiO$_2$, ZrO$_2$ and Al$_2$O$_3$

Alkoxide: Titanium n-butoxide, Zirconium n-butoxide, Aluminium tri-sec-butoxide

Stabilizers: $\beta$-diketones and $\beta$-ketoesters

Solvents: Methanol, Ethanol, Iso-propyl alcohol

Glove Box <5% relative humidity

alkoxide + stabilizer + solvent

Mixing for 2 hours

Ratio of alkoxide to stabilizer typically 1:1
Sub-10 nm lines of TiO$_2$ using a Leica VB6-UHR Nanowriter

Sub-10 nm lines of ZrO$_2$ using a Leica VB6-UHR Nanowriter

Resist Preparation

Alkoxide Route \((\text{TiO}_2, \text{ZrO}_2, \text{Al}_2\text{O}_3)\)

Naphthenate Route \((\text{ZnO})\)
What are metal naphthenates?

Metal naphthenates consist of cyclopentanes or cyclohexanes, methylene chains \([\text{-}(\text{CH}_2)\text{-}]\), carboxylates and metals. They can be represented as:

\[
[(\text{cyclopentane}) - (\text{CH}_2)_n - \text{COO}]^{-m} - \text{M}^{m+}
\]

where M is a metal atom.

They are sticky liquids at room temperature and are stable in air. Hence they do not require any special treatment like alkoxides.
E-beam damage of zinc naphthenate resist

Previous infrared studies suggest that the exposure of naphthenate molecules to an e-beam results in building bridges between them at the \(-\text{C}=\text{O}\)- and/or \(-\text{CH}_2\text{CH}_2\)- groups thereby increasing the molecular weight of the resist. This makes electron-beam exposed naphthenate resists insoluble in toluene.

Zinc naphthenenate

X-linking occurs here
Process details

- Zinc naphthenate (67 wt.-% in mineralised spirits) diluted 1:20 in toluene.
- Filter and spin coat @ 4000rpm for 30s (~90nm thick).
- Expose at 30mC.cm⁻² using 100kV 1.5nA beam.
- Develop in toluene for 10s
- Blow dry (no rinse)
- Characterise using DI Nanoscope™ AFM and LEO1530VP SEM.
Sensitivity at half the normalized thickness is 15 mC cm\(^{-2}\) and the contrast (\(\gamma\)) is 3.3.

## Comparative study of sensitivities

<table>
<thead>
<tr>
<th>Resist</th>
<th>Sensitivity</th>
<th>Type</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiO$_2$</td>
<td>35 mC cm$^{-2}$</td>
<td>Negative</td>
<td>100 kV</td>
</tr>
<tr>
<td>ZrO$_2$</td>
<td>40 mC cm$^{-2}$</td>
<td>Negative</td>
<td>100 kV</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>20 mC cm$^{-2}$</td>
<td>Negative</td>
<td>100 kV</td>
</tr>
<tr>
<td>ZnO</td>
<td>15 mC cm$^{-2}$</td>
<td>Negative</td>
<td>100 kV</td>
</tr>
<tr>
<td>Calixarene</td>
<td>20 mC cm$^{-2}$</td>
<td>Negative</td>
<td>70 kV</td>
</tr>
<tr>
<td>SAL-601</td>
<td>0.07 mC cm$^{-2}$</td>
<td>Negative</td>
<td>70 kV</td>
</tr>
<tr>
<td>HSQ</td>
<td>0.7 mC cm$^{-2}$</td>
<td>Negative</td>
<td>100 kV</td>
</tr>
<tr>
<td>PMMA</td>
<td>0.6 mC cm$^{-2}$</td>
<td>Positive</td>
<td>100 kV</td>
</tr>
</tbody>
</table>
Sub-10 nm lines of ZnO using a Leica VB6-UHR Nanowriter
Sub-10 nm lines of ZnO in the 500 µm main field
High aspect ratio structures

Aspect Ratio (for narrowest features) > 11
Post Development Bake studies on zinc naphenate resist
TGA & DTA studies of zinc naphthenenate resist

Heat Treatment Temperature = 500 °C

Heat Treatment at 500°C gives polycrystalline films of ZnO. Z = ZnO, S = Substrate and X = Contamination peaks
Optimization of Post Development Bake for photoluminescence in ZnO at 500°C

Peaks at 368nm (UV band-edge emission), 421nm (blue emission), 459nm (weak blue emission) and 501nm (green) were observed.

The presence of slightly broad peaks (368nm and 421nm) and visible range peak (501nm) suggest that the material still has some oxygen vacancies and other defects that cannot be completely removed by this 500°C heat-treatment process.
Sub-10nm lines of ZnO using a Leica VB6-UHR Nanowriter
Conclusions

- Sub-10 nm, high aspect ratio structures (>10) have been directly fabricated in ZnO by high resolution e-beam lithography using spin-coatable, zinc napthenate as a negative resist.

- Exposure to an electron beam makes napthenate based resists insoluble in organic solvents such as toluene.

- The electron beam sensitivity of these materials is comparable to that of conventional electron beam resists such as calixarene and other metallic oxide resists based on metallic alkoxides.

- Post development baking at 500°C for 1 hour in an argon/hydrogen ambient drives off the organic component of the resist, shrinking the feature size and drives the formation of the Zn-O bond enhancing the photoluminescence spectrum.

- The line edge roughness of the these patterns ~2.8nm (3σ) pre bake and ~2nm (3σ) post bake is the smallest measured value so far of any e-beam resist.