Diamond Science and Technology

Professor Haitao Ye
Chair of Materials Engineering

Inaugural Lecture
12th February 2019, Tuesday
I. Career profile

II. Diamond Science and Technology
   (a) Diamond for Gemstone
   (b) Diamond for Electronic Devices
   (c) Diamond for Cold Water Cleaning
   (d) Diamond for Antimicrobial Resistance

III. Summary
## I. Career Profile

<table>
<thead>
<tr>
<th>Year</th>
<th>Degree / Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994-1998</td>
<td>BEng in Xi’an Jiaotong University</td>
</tr>
<tr>
<td>1998-2000</td>
<td>MEng in Nanyang Technological University</td>
</tr>
<tr>
<td>2000-2004</td>
<td>PhD in University College London</td>
</tr>
<tr>
<td>2004-2005</td>
<td>Industrial Research Fellow at NTT corporation</td>
</tr>
<tr>
<td>2005-2009</td>
<td>Senior Research Fellow at London Center for Nanotechnology, Imperial and UCL (Visiting Fellow to CEA, France and AIST, Japan)</td>
</tr>
<tr>
<td>2009-2018</td>
<td>Lecturer/SL/Reader at Aston University</td>
</tr>
<tr>
<td>April 2018-</td>
<td>Chair in Materials Engineering</td>
</tr>
</tbody>
</table>
## I. Career Profile

<table>
<thead>
<tr>
<th>Professional esteem</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Income</strong></td>
</tr>
</tbody>
</table>
| **EBM**             | Diamond & Abrasives Engineering, Surface Technology
                      | Leading Guest Editor for MRS Focus Issue-2019 |
| **Membership**      | CEng (IET), DGA (GEM-A) |
| **Publication**     | > 100 journal papers & conference proceedings, H-index=20
                      | 1 book chapter
                      | 1 patent in Leicester-2019 |
| **Committee**       | 25th Congress of International Federation for Heat Treatment & Surface Engineering
                      | 5th International Workshop on Carbon based Nanomaterials & Nanostructures for Advanced Sensing
                      | 10th International Conference on New Diamond & Nano Carbons |
| **Supervision**     | Completion:5 PhD/ 2 PDRA/ 3 MC Fellow/ 10 Visiting Scholars |
| **Examiner**        | PhD examiner for UCL, UoB, CAS |
Mentors/ supporter 2000-2010

P. Hing  R.B. Jackman  K. Makoto  A.M. Stoneham
Note from Prof. Julia King, Baroness Brown of Cambridge

**Jellies!**

2nd July

Haitao

Not our greatest, but two - star performance!

Well done.

[Signature]
I. Career profile

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   (a) Diamond for Gemstone
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III. Summary
II. (a) Diamond as gemstone

*Diamonds are a girl’s best friend!*  
(Marilyn Monroe, 1953)
# II. (a) Diamond as gemstone (valuation)

## 4Cs OF DIAMOND QUALITY

<table>
<thead>
<tr>
<th><strong>Carat:</strong></th>
<th>Measures a Diamond’s Apparent Size</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Color:</strong></td>
<td>Actually Means Lack of Color</td>
</tr>
<tr>
<td><strong>Clarity:</strong></td>
<td>The Absence of Inclusions and Blemishes</td>
</tr>
<tr>
<td><strong>Cut:</strong></td>
<td>Unleashes Its Light</td>
</tr>
</tbody>
</table>
4Cs of gemstone diamond quality

1 carat = 0.2 gram
### 4Cs of Gemstone Diamond Quality

#### GIA Clarity Grading Scale

<table>
<thead>
<tr>
<th>GIA Clarity Grading Scale</th>
<th>FL-IF</th>
<th>VVS&lt;sub&gt;1&lt;/sub&gt;</th>
<th>VVS&lt;sub&gt;2&lt;/sub&gt;</th>
<th>VS&lt;sub&gt;1&lt;/sub&gt;</th>
<th>VS&lt;sub&gt;2&lt;/sub&gt;</th>
<th>SI&lt;sub&gt;1&lt;/sub&gt;</th>
<th>SI&lt;sub&gt;2&lt;/sub&gt;</th>
<th>l&lt;sub&gt;1&lt;/sub&gt;</th>
<th>l&lt;sub&gt;2&lt;/sub&gt;</th>
<th>l&lt;sub&gt;3&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clarity</td>
<td>Internally Flawless</td>
<td>Very Very Slight Inclusions</td>
<td>Very Slight Inclusions</td>
<td>Slight Inclusions</td>
<td>Imperfect</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### GIA Color Grading Scale

- **D**: Colorless
- **E**: Near colorless
- **F**: Faint yellow
- **G**: Very light yellow
- **H**: Light yellow
- **I**: Lesser
- **J**: Near fancy light yellow
- **K**: Fancy light yellow
- **L**: Fancy yellow
- **M**: Light orange yellow
- **N**: Yellow
- **O**: Light orange
- **P**: Orange yellow
- **Q**: Orange
- **R**: Yellow orange
- **S**: Light brown yellow
- **T**: Brown yellow
- **U**: Brown yellow
- **V**: Light brown
- **W**: Brown
- **X**: Brown red yellow
- **Y**: Brown yellow
- **Z**: Brown
4Cs of gemstone diamond quality
## Gemstone Diamond Types

<table>
<thead>
<tr>
<th>Diamond types</th>
<th>Type I (Nitrogen present as impurity)</th>
<th>Type II (Nitrogen absent)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type Ia (N as pairs or groups)</td>
<td>Type Ib</td>
</tr>
<tr>
<td></td>
<td>98% of all gem diamonds</td>
<td>0.1%</td>
</tr>
<tr>
<td>Type IaA</td>
<td>Type IaB</td>
<td>Type IaAB</td>
</tr>
<tr>
<td>nitrogen as N2</td>
<td>nitrogen as N4-V</td>
<td>(N as isolated atoms)</td>
</tr>
<tr>
<td>Colourless</td>
<td>Colourless to yellow</td>
<td>Yellow</td>
</tr>
<tr>
<td>Cape series</td>
<td>Canary yellow</td>
<td>Cullinan</td>
</tr>
<tr>
<td>Absorption peak: 415nm line</td>
<td>503nm &amp; 637nm</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td>1130cm(^{-1}) and 1344cm(^{-1})</td>
<td></td>
</tr>
</tbody>
</table>
Lab created diamonds, engineered or cultured diamonds, grown in highly controlled laboratory environments. They are made of the same material as natural diamonds, and exhibit the same optical and chemical properties.

De Beers: 1-carat synthetic sells for $4,000, about half the price of a natural diamond. De Beers new lab gems, to hit the market since Sep 2018, will sell for around $800 a carat.

Marlow's: Jewelry Quarter, Birmingham. Probably one of the best price in the UK market.
Synthetic Diamond

(1) Detonation
(2) HPHT
High Pressure High Temperature
(3) Chemical Vapor Deposition

Nanoparticle
Single crystalline
Thin film diamond
Single/Poly/Nanocrystalline
Phase diagram of diamond

Detonation

Natural

HPHT

CVD

Synthetic Diamond - CVD

- CVD is a chemical process
- Produce thin film on substrates
- Homoepitaxial/ Heteroepitaxial
- \( \text{CH}_4 + \text{H}_2 \Rightarrow \text{diamond (sp}^3/\text{sp}^2) + \text{radicals} \)
- Conductivity (doping: B, P, N)
- Surface energy
Synthetic Diamond

Polycrystalline
SCT 123 (2000) 129

Preferential oxidation
JPD 33 (2000) 2196

Nanocrystalline
JAP 94 (2003) 7878

Nanodiamond particles
APL 93 (2008) 132115

Nanodiamond particle
JAP 113 (2013) 023707

On fibrous substrates
JAP 113 (2013) 024313

Polycrystalline
Vacuum 122 (2015) 342

Single crystal
JCG 434 (2016) 36
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III. Summary
# Diamond electronic properties

<table>
<thead>
<tr>
<th></th>
<th>Diamond</th>
<th>Si</th>
<th>SiC-6H</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band gap (eV)</td>
<td>5.5</td>
<td>1.1</td>
<td>2.9</td>
<td>3.44</td>
</tr>
<tr>
<td>Breakdown field (MV/cm)</td>
<td>10</td>
<td>0.3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Electron mobility (cm²/Vs)</td>
<td>4500</td>
<td>1450</td>
<td>500</td>
<td>400</td>
</tr>
<tr>
<td>Hole mobility (cm²/Vs)</td>
<td>3800</td>
<td>480</td>
<td>70</td>
<td>200</td>
</tr>
<tr>
<td>Thermal $K$ (W/cmK)</td>
<td>24</td>
<td>1.5</td>
<td>5</td>
<td>1.3</td>
</tr>
<tr>
<td>Johnson’s FOM</td>
<td>95</td>
<td>1</td>
<td>26</td>
<td>17</td>
</tr>
<tr>
<td>Keye’s FOM</td>
<td>31</td>
<td>1</td>
<td>5.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Baligas FOM</td>
<td>17200</td>
<td>1</td>
<td>670</td>
<td>910</td>
</tr>
</tbody>
</table>
II. (b) Diamond for Electronic Devices

- 1. Diamond UV photodetectors
- 2. Diamond Power Devices
1. Diamond UV photodetectors

- Photoconductive design
  - Interdigitated structure
  - Gold electrodes
  - 25µm pitch
  - Freestanding CVD diamond (~100µm thick)

- Many regions are single crystal
1. Diamond UV photodetectors

- As fabricated device responsive in the visible
- Magic treated device shows true ‘visible blindness’
- Sharp cut off at band edge (225nm)

- UCL Patent licensed to Centronic Ltd, UK
1. Diamond UV photodetectors

- The application of post-growth treatments have enabled us to ‘engineer’ the properties of the devices
  - Spectral characteristics
  - Speed
  - Gain
  - Radiation hardness
  - Dark current

- Commercially under licence to Centronic Ltd.
2. Diamond Power Devices for Telecommunication

![Graph showing output power and operating frequency for different devices and semiconductor materials.]

Diamond will replace traveling-wave tubes now used for RF high-power applications.

Fig. 1 Output power and operating frequency currently required for specific devices in systems along with the semiconductor materials, NTT Technical Review 8 (2010) 1.
2. Diamond Power Devices: MESFETs

1. Gate length ($L_G$)

2. Gate materials

3. Source-Gate Resistance

Challenge: substrate size, crystal quality, doping technique, interface control, surface control, stability (high $k$ dielectrics as gate).

Factors for high RF performance:

1. Gate length ($L_G$)
2. Gate materials

Challenge:

- Substrate size
- Crystal quality
- Doping technique
- Interface control
- Surface control
- Stability (high $k$ dielectrics as gate)
2. Diamond Power Devices: MESFETs

First demonstration of diamond power devices with the record-high output power and record-high operating frequency in the world-wide diamond research community. Still the highest!

Two times higher than GaAs widely used at present

\[ \text{PAE: power added efficiency} = \frac{P_{\text{OUT(RF)}} - P_{\text{IN(RF)}}}{P_{\text{(DC)}}} \]
2. Diamond Power Devices: MESFETs

\[ P_{\text{OUT}} = 0.84 \text{ W} \]

\[ \Delta T = 0.64^\circ \text{C} \]

\[ T_{\text{FET}} = 26.20^\circ \text{C} \]

\[ T_{\text{FET}} = 25.56^\circ \text{C} \]

Cf. GaAs MESFET \((K = 0.46 \text{ W/cmK})\)

\[ P_{\text{OUT}} = 0.84 \text{ W} \]

\[ \Delta T = 42^\circ \text{C} \]

\[ L = 0.4 \mu\text{m} \]

\[ W_{\text{G}} = 200 \mu\text{m} \]

\[ K = 22 \text{ W/cmK} \]
Si is to stay as the core substrate material for the majority of power semiconductor devices.

SiC, now entering the market, will grow in importance to complement silicon. SiC may offer particular advantage at higher voltages and temperatures although, so far, it has not been able to deliver the much needed jump to 10kV+ devices.

GaN technologies look set to significantly impact power devices up to voltages of 1200V, notably for integrated power applications.

Diamond is another material of promise, notably for high-voltage and high frequency applications. This is a potentially disruptive technology.
H2020 D-SPA Project Project (no: 734578)

- Diamond based nanomaterials and nanostructures for advanced electronic and photonic applications (D-SPA)
- Overall budget EUR 1.1 M with Leicester as the PI
- 4 year project (2017-2021)
- 9 Consortium members in Spain, Ireland, UK, USA, China

- www.d-spa.org
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III. Summary
II. (c) Diamond for Cold Water Cleaning
II. (c) Surface Functionalized Nanodiamonds: why ND?

- Possess hydrophobic feature;

- Large surface area that can adsorb lipid /small molecules;

- Opportunities for further modification/functionnalization to tune surface properties;

- ND self-aggregation can be mitigated by surface modification and surfactant additives for a stabilized ND suspension.
II. (c) Surface Functionalized Nanodiamonds

Processing:
1) Oxidation (ND-1)
2) Hydrogenation (ND-2):
   2.1 Alkyl- (ND-3)
   2.2 Amine- (ND-4)

Characterisation:
1) TEM
2) Impedance Spectroscopy
3) XPS
4) FTIR
5) Zeta Potential
II. (c) Surface Functionalized Nanodiamonds

Lipid removal (R1) by surfactants SDBS or G$_1$C$_{10}$ in the presence of ND97 at 25 & 15 °C.

II. (c) Surface Functionalized Nanodiamonds: impact

Nanodiamond for improving Cold Water Cleaning

Mail Online

Diamonds, a washer woman's best friend: Microscopic sparklers in washing powder help detergents work much more effectively

By Daily Mail Reporter

PUBLISHED: 00:26 GMT, 26 June 2012 | UPDATED: 09:37 GMT, 26 June 2012

They are already known as a girl's best friend. Now it seems diamonds could soon be her favourite stain remover, too.

Chemists added small amounts of nanodiamonds – pieces of carbon less than a ten-thousandth of the diameter of a human hair – to commercial washing powders.

They found the diamonds made the detergent much more effective at removing dirt and grease, even at 15C.
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III. Summary
II. (d) Antimicrobial Resistance (AMR)

- AMR as one of the main challenges facing the 21\textsuperscript{st} century.

- In the fight against AMR, different possibilities have been explored:
  - Search for new efficient antibiotics
  - Develop fast and specific diagnostics to restrict the use of antibiotics
  - Nanomaterials and nanostructures, to destroy or inhibit the growth of bacterial strains
II. (d) Antimicrobial Resistance (AMR)

Ag, Cu, ZnO, Fe$_3$O$_4$, Al$_2$O$_3$, TiO$_2$, SiO$_2$

For practical application
- Broad availability
- Easy and Stable surface functionalities
- Dispersibility in aqueous solution
- Non-toxic
- Environmental friendly

Nanodiamond based platform for antimicrobial resistance receiving increased attention
II. (d) Antibacterial mechanism based on Chemical interactions

<table>
<thead>
<tr>
<th>ND&lt;sup&gt;+&lt;/sup&gt;</th>
<th>ND&lt;sub&gt;raw&lt;/sub&gt;</th>
<th>ND&lt;sub&gt;raw,n.u.&lt;/sub&gt;</th>
<th>ND&lt;sub&gt;pure-air/450°&lt;/sub&gt;</th>
<th>ND&lt;sub&gt;pure+ H₂/500°&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>air annealed/450°C</td>
<td>no annealing</td>
<td>no annealing and sonication</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ζ = -44 eV</td>
<td>ζ = n.d.</td>
<td>ζ = n.d.</td>
<td>ζ = +63 eV</td>
<td>ζ = +80 eV</td>
</tr>
</tbody>
</table>

| S. aureus | dead | dead | viable | viable |
| E. coli | dead | dead | viable | viable |

**Figure:** Antibacterial effect of different NDs: (A) Antibacterial activity of differently oxidized NDs on *E. coli* (a) and *B. subtilis* (b) evaluated using the adenosine triphosphate (ATP) level as marker for vital bacterial metabolism; (B) Antibacterial activity of ND-COOH, ND-NH2, ND-OH and ND-mannose ND-mannose determined from fluorescence images using Dead/Live assays.
Preliminary results: Mushroom structures
Aston Multidisciplinary Research for Antimicrobial Resistance, the AMR4AMR project, is generating an active and vibrant research environment that brings together researchers from across Aston to focus holistically on the problem of antimicrobial drug resistance to find new and innovative solutions.

- 2015-2018
- £730k
INNOVATE UK ANCOP project

- Industrial Challenge Programme
- Antimicrobial Coatings by PVD and CVD for application in aerospace (ANCOP),
- 30 month project (2018-2020)
Summary

Diamond Science and Technology

(a) Diamond for Gemstone
(b) Diamond for Electronic Devices
(c) Diamond for Cold Water Cleaning
(d) Diamond for Antimicrobial Resistance

Diamond also comes with man-made varieties which offer much more potential than their gemstone namesake.
• Dr. X. Chen, Edinburgh University
• Prof. Ran Liu, Fudan University
• Prof. P. Lambert, Aston University
• Dr. Tomasz Ochalski, National Institute of Tyndall, Ireland
• Prof. C.Z. Gu, Institute of Physics, CAS, RAEng
Distinguished Visiting Fellow
The Science and Technology of Vapor Phase Processing and Modification of Surfaces
FOCUS ISSUE • MARCH 2020

Surface modification tools such as plasma enhanced physical vapor deposition and chemical vapor deposition processes, high energy ion implantation, high-power impulse magnetron sputtering, plasma electrolysis and discharge deposition have resulted in significant improvements in material properties for biomedical devices, MEMS, bearings, and cutting tools. These advances have been enabled by the development of new thin film deposition approaches, epitaxial schemes, multi-structured buffer layers, computation simulations, and new analytical probes to investigate the details of interface chemistry and structure. While many advances have been empirical, scientific understanding of the behavior of such surface modified materials is needed to accelerate further progress.

This JMR Focus Issue solicits papers that report advances in the synthesis, processing, and performance of materials enhanced by vapor phase processes. Special attention will be given to papers focused on surface reaction dynamics and film growth, the science and technology of surfaces and interfaces, and the mechanism of property enhancement.

- Plasma Surface treatment
- High energy ion implantation
- Utilization of novel buffer layers
- High-power impulse magnetron sputtering
- Plasma electrolysis and discharge deposition
- Novel technologies for hard and super-hard thin films
- Applications of computational modeling
- Analytical tools for interface characterization

GUEST EDITORS
Haitao Ye, University of Leicester, United Kingdom
Chengming Li, University of Science and Technology, China
Sarah Hainsworth, Aston University, United Kingdom

Submission Deadline—August 1, 2019
Journal of Materials Chemistry A - Invitation to submit a review

Journal of Materials Chemistry A <onbehalfof@manuscriptcentral.com>

Mon 28/01/2019 12:57

To: Ye, Haitao (Prof.) <haitao.ye@leicester.ac.uk>;

28-Jan-2019
Dear Dr Ye

We are delighted that you have accepted our invitation to submit a review to Journal of Materials Chemistry A.

Please use the following link to submit your review article: https://emea01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fmc.manuscriptcentral.com%2Fjmchema%3FURL_Mask%3D6c2ab5a221434b92ba253ec3ee9e54ac%26data=02%7C01%7Chaitao.ye%40leicester.ac.uk%7Cc3f4a627f8c54be7035d08d685202128%7Caebec6d44b0195c8274afe853d9%7C0%7C0%7C636842770375860206%26sdata=bARMp%2BXi b1r8KgZqURF1dzQPJUi8pYg857LQWaBmVXU%3D%26reserved=0

We look forward to receiving your submission in due course.

Yours sincerely,

Rose Wedgbury PhD MRSC
Development Editor, Journals
Journal of Materials Chemistry A, B & C
MaterialsA-rsc@rsc.org
Thank you!