HD STRAIN
3D strain metrology for electronic devices

01/01/2009 -> 30/09/2013

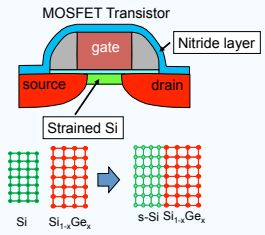
AGENCE NATIONALE DE LA RECHERCHE ANR

Develop Dark-Field Electron Holography (HoloDark) for Strain Metrology in Devices
- Methodology: 2D → 3D measurements
- Instrumentation: brighter electron sources, in-situ experiments
- Characterisation: model → industrial specimens

➡ *reliable and robust technique for strain measurements*

CEMES Toulouse | LETI Grenoble | Crolles Grenoble

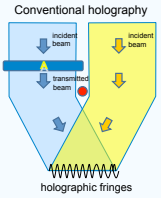
Strained Silicon

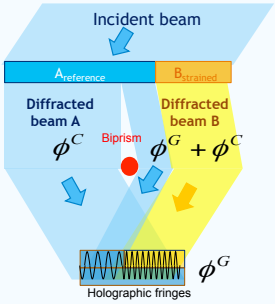


- Strained silicon channel
- Strain engineering methods include embedded sources and strain layers; technology which is industrial standard
- Straining silicon increases carrier mobility (electrons or holes)

➡ *need for measurement*

Dark-Field Electron Holography

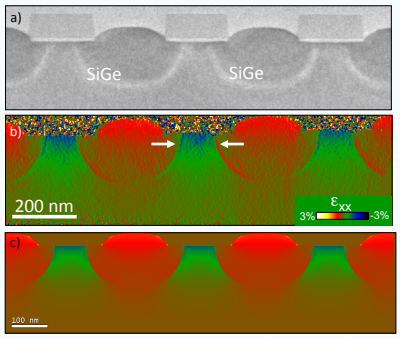




- New technique interferes diffracted beams from unstrained (A) and strained (B) regions
- Advantages include: µm-field of view, high spatial resolution and high precision

HoloDark 1.0 software (HREM Research Inc.) by M J Hÿtch, C Gatel, K Ishizuka

Strain Mapping



a) TEM micrograph b) Experimental strain map c) FEM of strain

M J Hÿtch, F Houdellier, F Hüe, E Snoeck, **Nature** 453, 1086 (2008)

F Hüe, M J Hÿtch, F Houdellier, H Bender, A Claverie, **APL** 95, 073103 (2009)

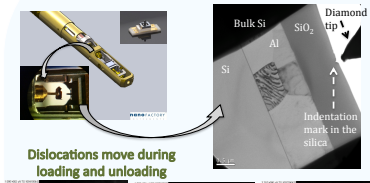
M J Hÿtch et al. **Physica Status Solidi A** 208, 580 (2011)

M J Hÿtch, F Houdellier, F Hüe, E Snoeck, **Ultramicroscopy** 111 1328-1337 (2011)

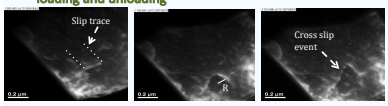
International Patent Application: PCT N° PCT/FR2008/001302 (CNRS)

In situ TEM measurements and finite element modelling

IN SITU TEM NANOINDENTATION

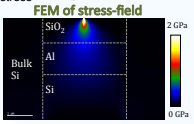


Dislocations move during loading and unloading



- Slip-traces + stereographic projection map -> slip plane (111)
- Cross-slip event -> Burgers vector **b**=[01-1]
- Resolved shear stress $\tau = \mu\|\mathbf{b}\|/R = 200$ MPa
- Applied force **T**=[103] -> Schmid factor $S = \cos(\mathbf{T},\mathbf{b})\cdot\cos(\mathbf{T},(111)) = 0.48$
- Shear stress $\sigma = \tau / S = 400$ MPa

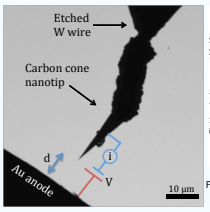
FEM of stress-field

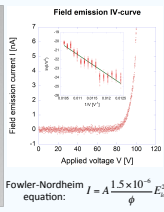


- External stress with 150 µN applied force -> 2-300 MPa in Al layer

L de Knoop, S Reboh, M Legros

IN SITU TEM FIELD EMISSION AND ELECTRON HOLOGRAPHY





$d + \gamma \rightarrow$ work function ϕ

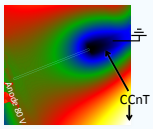
$E_{tip} = \gamma E_0 = -\gamma \frac{V}{d}$

Phase $\varphi = C_E \int V\,dl$

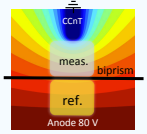
$d = 680$ nm, $\gamma = 21.5$ → $\phi = 4.8 \pm 0.3$ eV

Fowler-Nordheim equation: $I = A\frac{1.5\times10^{-6}}{\phi}E_{tip}^2 \exp\left(\frac{10.4}{\sqrt{\phi}}\right)\exp\left(-\frac{6.44\times10^9\phi^{1.5}d}{\gamma V}\right)$

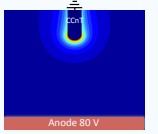
Phase shift from EH

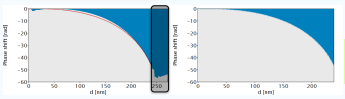


Phase shift from FEM



Electric field from FEM

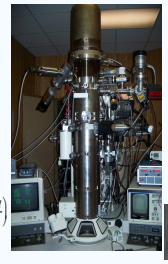


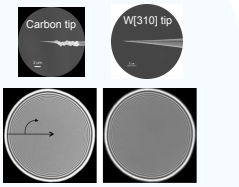


$\gamma = \frac{E_{tip}}{E_0} = \frac{2.58}{0.12} \approx 21.5$

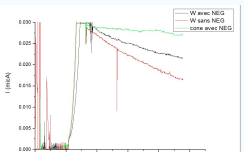
L de Knoop, F Houdellier, C Gatel, A Masseboeuf, M Monthioux, M J Hÿtch

Brighter electron source





HIGH COHERENCE



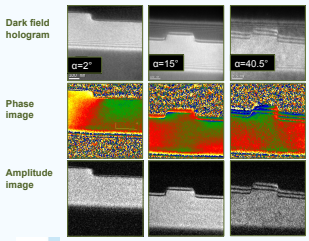
Emission current = 8 µA
Exposure = 1 s
C_2 aperture = 50 µm

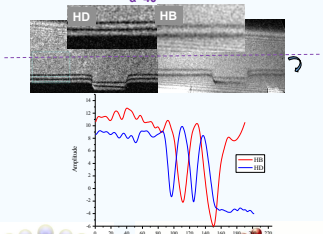
F Houdellier, A Masseboeuf, M Monthioux, M J Hÿtch, **Carbon** 50 (2012)
Development of a New Cold Field-Emission Gun for Electron Holography.

F Houdellier and M Monthioux, *French Patent Application*, FR 10 03696, 2010 (CNRS)

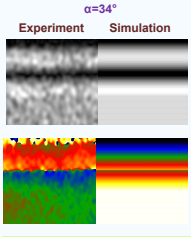
Tomography

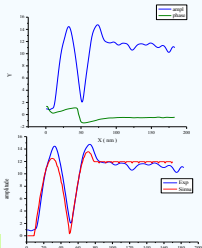
FIRST DARK-FIELD ELECTRON HOLOGRAPHY TOMOGRAPHY EXPERIMENTS





COMPARISON WITH DYNAMICAL SIMULATIONS





E Javon, C Gatel, A Lubk, M J Hÿtch

CEMES TOULOUSE

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