Moiré Principle Illustrated

\[
P = \left| \frac{p_1 p_2}{|p_2 - p_1|} \right|
\]

Position (phase) of moiré fringes is very sensitive to relative position of \( p_1 \) and \( p_2 \)

Moiré Pattern:

- \( (\text{not resolvable in optical microscope}) \)
- \( (\text{not resolvable in optical microscope}) \)
- \( (\text{easily resolved in optical microscope}) \)
Moiré Stitching Measurement

Diagram of Single e-beam Field

Edges of adjacent fields overlap, generating a moiré pattern.

Phase of moiré pattern indicates the amount of transverse stitching error.

Reference moiré fringes provide a basis for comparison.
**Illustration of Stitching Measurement**

No Stitching Error vs Stitching Error

\[
\Delta x = \delta \frac{P}{p_i}
\]

Magnification Factor
Optical Micrograph of Field Boundaries

100 µm
Horizontal Boundary Between Fields

optical micrograph (20X 0.4 NA objective lens)

$p_1 = 189$ nm
$p_2 = 195$ nm
$P = 6.05$ µm
field size = 100 µm

visually: can resolve fringes to $\sim P/10$ ($\sim 20$ nm stitching resolution)
Measurement of Spatial Phase using offline FFT method:

1. \( F[k] = \text{FFT}(f[n]) \)  
   *compute spectrum of signal*

2. \( k_0 = \arg \max |F[k]| \)  
   *find peak in spectrum*

3. \( f = \text{angle} (F[k_0]) \)  
   *compute spatial-phase*

Can resolve fringes to \( \sim P/100 \)  
(\( \sim 2 \text{ nm stitching resolution} \))
Line Profile of Moiré Images

**A**
Top Reference

**B**
Middle Moiré Pattern

**C**
Bottom Reference

stitching error = 18 ± 2 nm
Moiré Fringe Discontinuity

*Computed via FFT*

![Graph showing phase offset (fringes) vs. x (µm)]
**Moiré Technique vs Vernier Measurement**

Optical Micrograph of Field Boundary (20X, 0.4 NA objective)

![Optical Micrograph of Field Boundary](image)

SEM of Vernier Marks (after liftoff of Chromium)

- \( p_1 = 189.2 \text{ nm} \)
- \( p_2 = 195.3 \text{ nm} \)
- \( \Delta p = 6.1 \text{ nm} \)

Moiré Fringe Discontinuity (computed via FFT)

- \( \Delta x = 37 \pm 6 \text{ nm} \)
- \( \Delta x = 35 \pm 2 \text{ nm} \)
Application: Measuring Stitching Statistics

wrote 8 x 8 array of 100 µm fields on VS2A e-beam system
stitching error measured at each boundary using moiré technique

Horizontal Stitching

\[ m_x = 23 \text{ nm} \]
\[ \sigma_x = 16 \text{ nm} \]

Vertical Stitching

\[ m_y = -15 \text{ nm} \]
\[ \sigma_y = 7 \text{ nm} \]
Application: Investigation of Field Distortion

Measure Stitching Error at Several Points along 400 µm Field Boundary

Infer Amount of Intra-field Distortion

Position Along Field Boundary

Stitching Error (nm)
Summary of Features

- **SENSITIVE**: 2 nm resolution (better than Vernier method)
- **CONVENIENT**: Requires no liftoff or post-exposure pattern transfer
- **INEXPENSIVE**: uses only a conventional optical microscope