# High-Q Inductor Modeling on Locally Semi-Insulated Si CMOS Substrate by Helium-3 Bombardment

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Matsuzawa
& Okada Lab.

# Outline

- ◆Background
- ◆Motivation
- ◆Conventional methods to improve inductor quality factor
- ◆Helium-3 bombardment
- ◆Simulation and experimental results
- ◆Inductor modeling
- ◆Conclusions

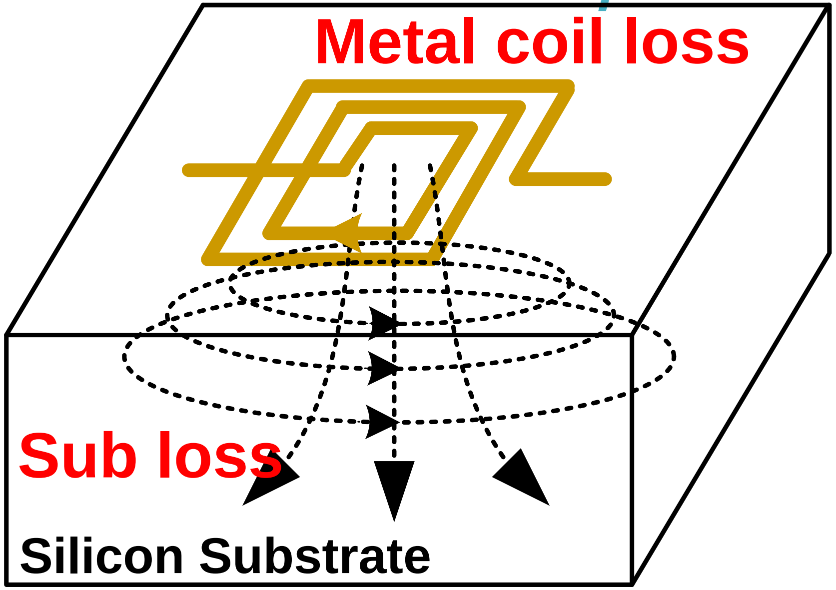
# Background

- **CMOS on-chip inductors are indispensable for RF circuits.**
  - **High integration**
  - **No need for 50-Ω interface**
  - **VCOs, LNAs, PAs, etc**

- **RF circuits suffer from the poor performance.**
  - **Thin metal line**
  - **Low substrate resistivity less than 10Ω·cm**
  - **Q is around ten for on-chip inductor.**

# Inductor Loss Mechanisms

- ◆ **Losses by currents in metal coil**
  - ➢ **Ohmic loss, skin effect, proximity effect**
  - ➢ **Improved by using thick metal**
- ◆ **Substrate loss**
  - ➢ **Eddy currents in substrate**



$$Q(\omega) \cong \frac{\omega L}{R}$$

**Q: quality factor**
**ω: frequency in radius**
**L: inductance**
**R: parasitic resistance**

Ref.: Bunch, IEEE Microwave magazine June 2002.

# Motivation

◆Improve quality factor of on-chip inductors by decreasing silicon substrate loss

◆Ensure circuits working well

- ➢No damage on active devices

# Conventional Methods to Improve Q

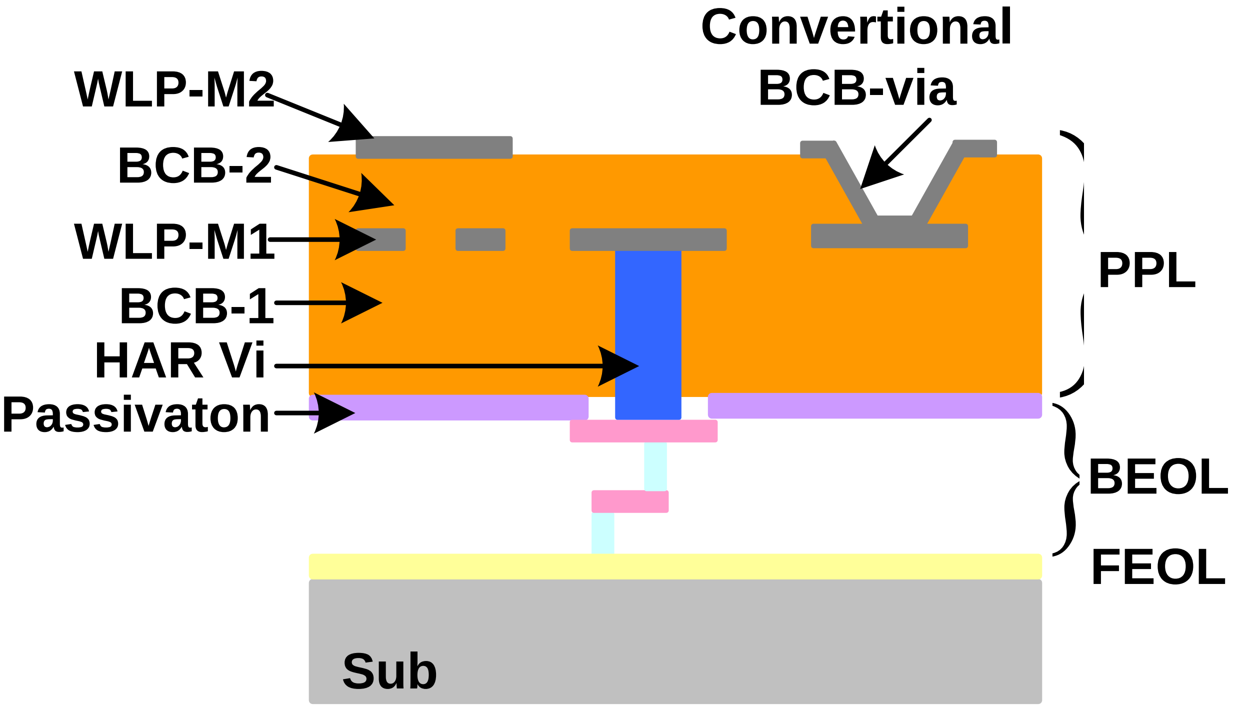
◆Post-passivation interconnect (PPI)

◆Proton bombardment

# Conv. Meth. to Improve Q (Cont’d)

## ◆Post-passivation interconnect (PPI)

- limited to wafer level packaging (WLP)
- Large parasitic from the high aspect ratio via (HAR vi)

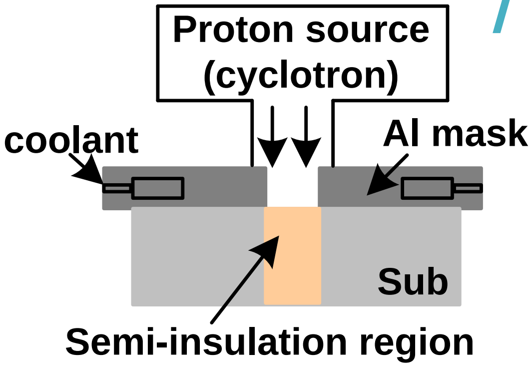


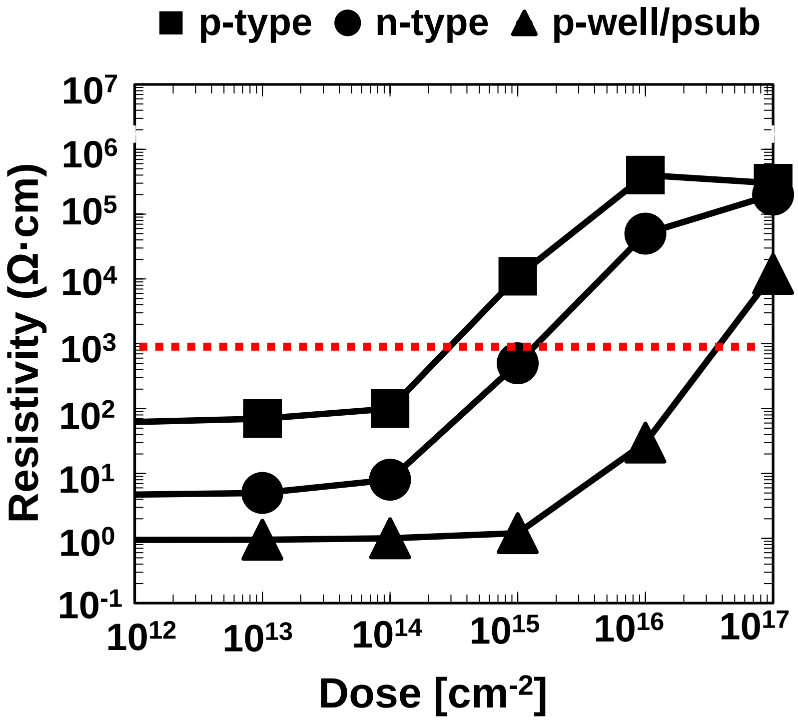
Schematic Cross section of PPI

Ref.: [1], C. C. Liu et al., IEDM 323, 2012. [2], G. J. Carchon, et al., MTT 2004

# Conv. Meth. to Improve Q (Cont'd)

- **Proton bombardment**
  - Good performance
  - Large dose
    - For $R_{sub}$>1kΩ, about $10^{15}$cm$^{-2}$
  - High cost
    - $10^{15}$-cm$^{-2}$ dose needs more than 3h.
  - Poor reliability
    - 50-µm margin





Ref.: [1], L. S. Lee, et al., TED 2001. [2] D. D. Tang, *et al*, IEDM 2003.

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# Why Helium-3?

| Method | Reliability | Cost | Q improvement |
|---|---|---|---|
| Thick metal[1] | Good | Fair | Good (thickness limitation) |
| PPI[2] | Good | High | Good (Package limitation) |
| Silicon on Insulator[3] | Good | Very High | Fair(failed in high freq.) |
| Proton[4] | Poor | High | Good |
| Helium-3 (This work) | Good | Fair | Good |

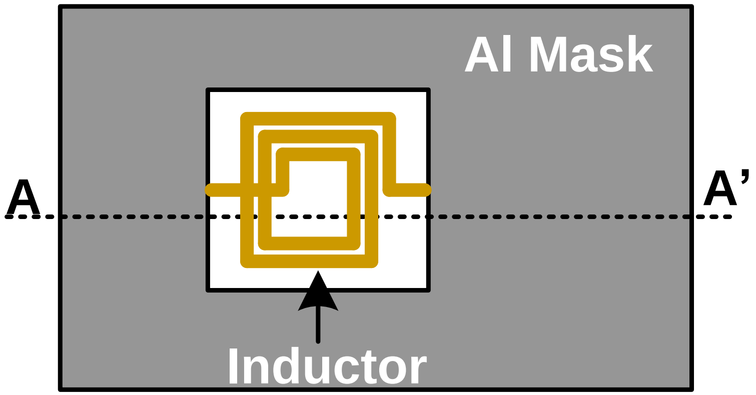
## Compared to Proton, Helium-3

◆ higher vacancies generation ability
◆ higher irradiation efficiency
◆ high throughput
◆ less lateral scattering
◆ less dose
◆ less process cost

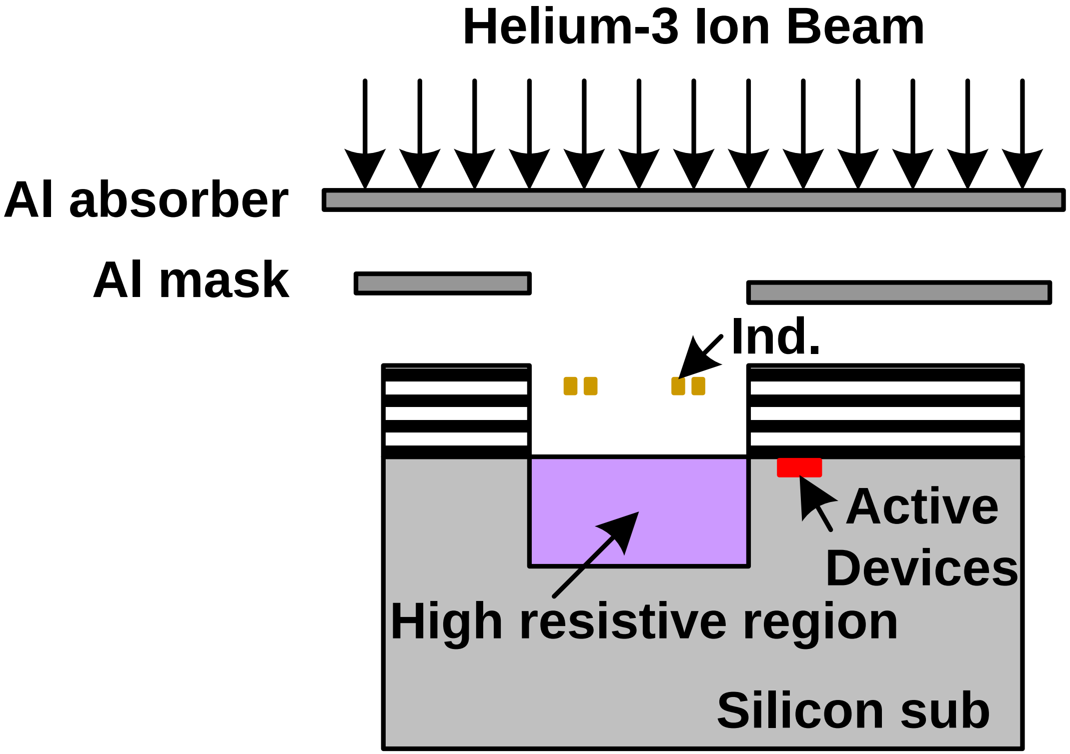
Ref.: [1], J. R. long, et al., JSSC 1997. [2], C. C. Liu, et al., IEDM 2012.
[3], J. H. Kim, et al., RFIC 2003. [4], L. S. Lee, et al., TED 2001.

# Helium-3 Bombardment

- ◆Improving substrate resistivity
- ◆500-μm Al mask is used to protect active devices.

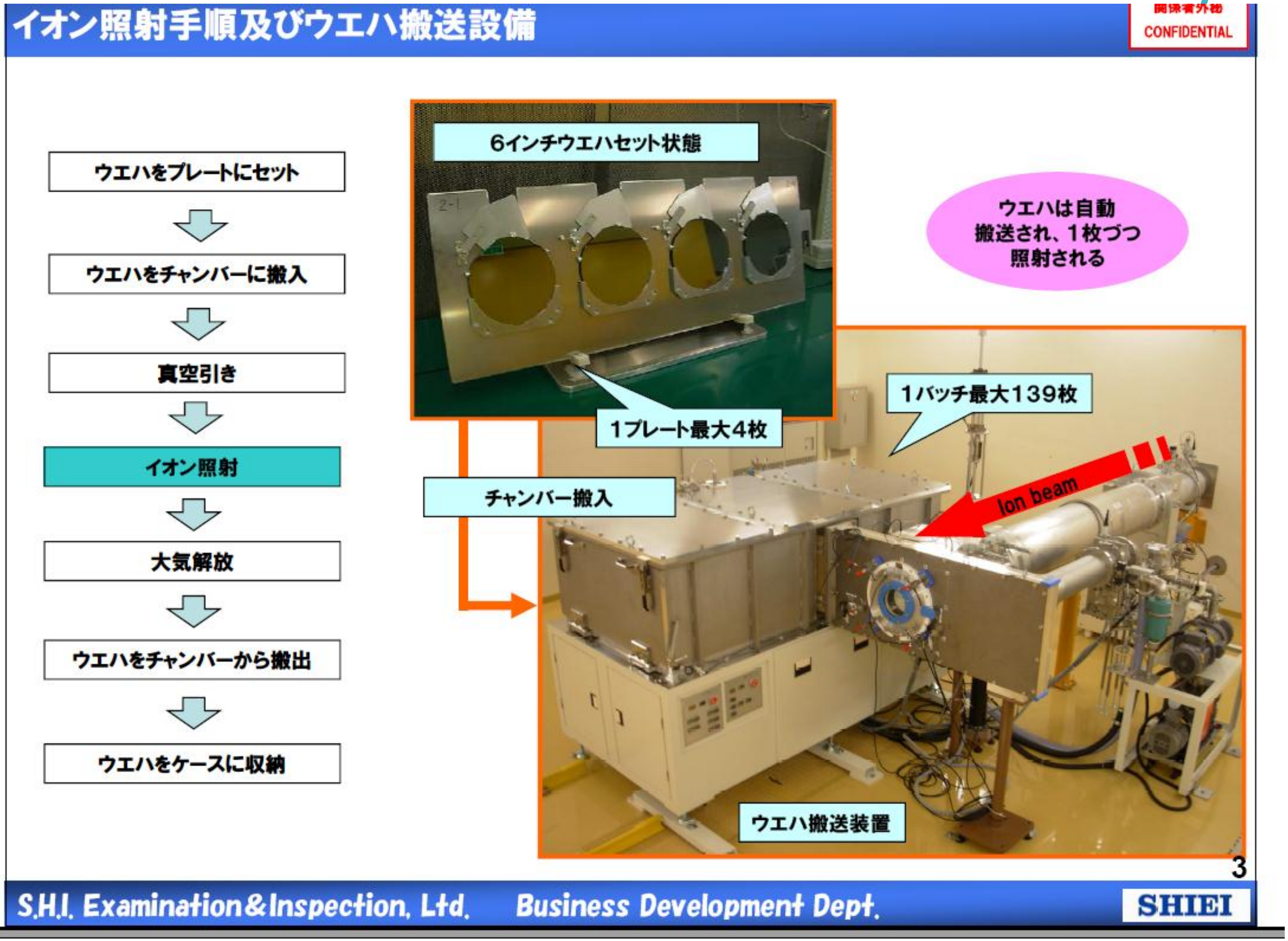


Top view



Cross view

# Helium-3 Bombardment (Cont'd)



## イオン照射手順及びウエハ搬送設備

関係者外秘
CONFIDENTIAL

ウエハをプレートにセット
↓
ウエハをチャンバーに搬入
↓
真空引き
↓
イオン照射
↓
大気解放
↓
ウエハをチャンバーから搬出
↓
ウエハをケースに収納

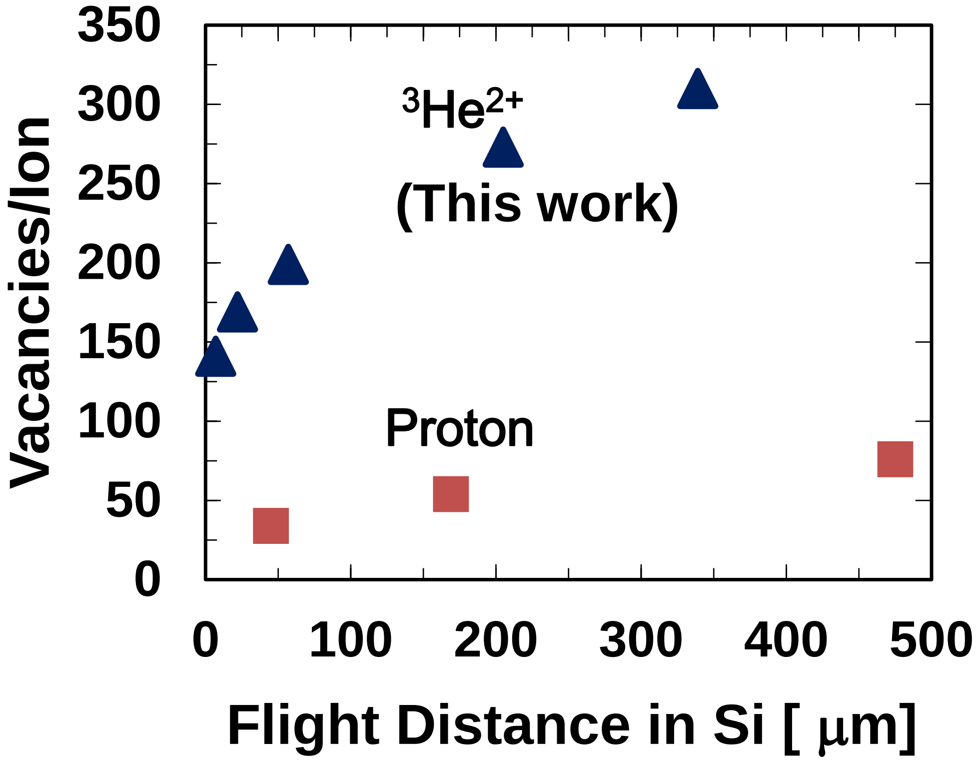
ウエハは自動
搬送され、1枚づつ
照射される

S.H.I. Examination&Inspection, Ltd.　Business Development Dept.　SHIEI

3

# Vacancy Generation per Ion

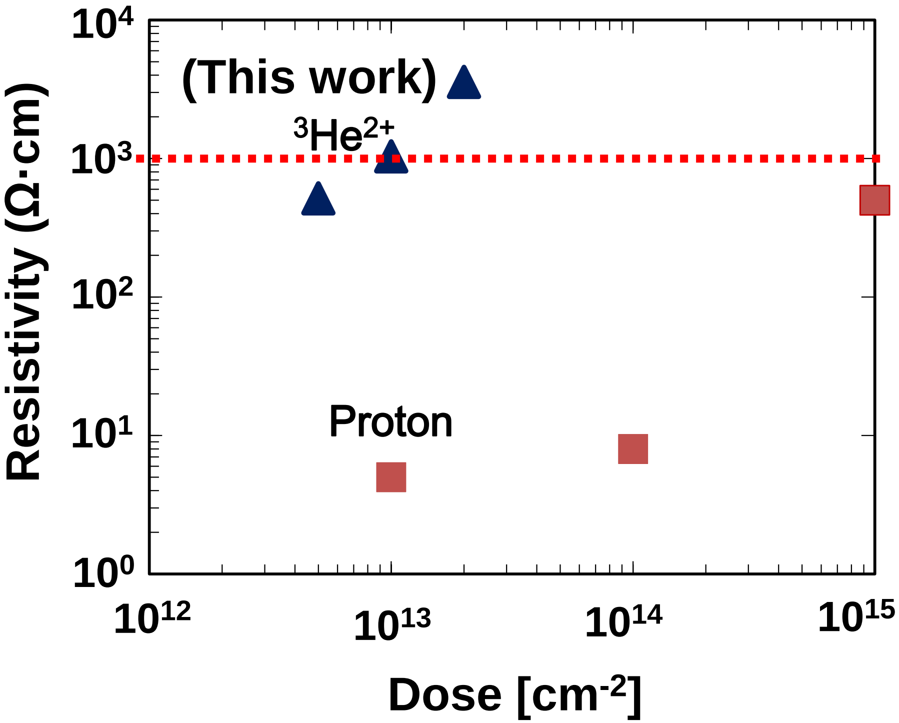
- ◆Larger vacancy generation per ion at the same flight distance in silicon
- ◆Vacancies/ion of Helium-3 is more than 5~6 times larger than that of proton



Calculated by Transport of ions in matter (TRIM) of a software named Stopping and Range of Ion in Matter (SRIM)

# Resistivity

- ◆ Small dose
  - ➢ For $R_{sub}$>1kΩ, about $10^{13}$cm$^{-2}$
- ◆ lower cost
  - ➢ $10^{13}$-cm$^{-2}$ dose needs only 3.7min

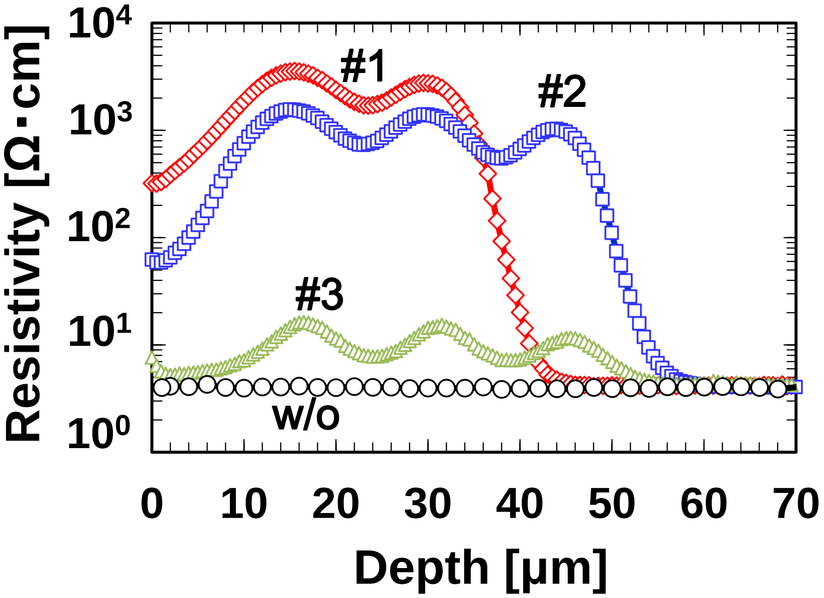


CZ-N wafer
Boron dopant
1x$10^{15}$ atms/cm$^3$

Ref.: L. S. Lee, et al., TED, 2001

# Substrate Resistivity Profile

- Spreading resistance profiler (SRP) method
- Larger dose, higher substrate resistivity
- Peaks are correspond to implantation times and depth.
- About $10^{13}$cm$^{-2}$ dosing twice realizes a 30-μm high resistivity region above 1kΩ. (red line)



| Cond. | Total time [s] | Target irradiation depth [μm] | Total dose [cm$^{-2}$] |
|---|---|---|---|
| #1 | 444 | 15, 30 | 2.0 x$10^{13}$ |
| #2 | 332 | 15, 30, 45 | 1.5 x$10^{13}$ |
| #3 | 66 | 15, 30, 45 | 3.0 x$10^{12}$ |

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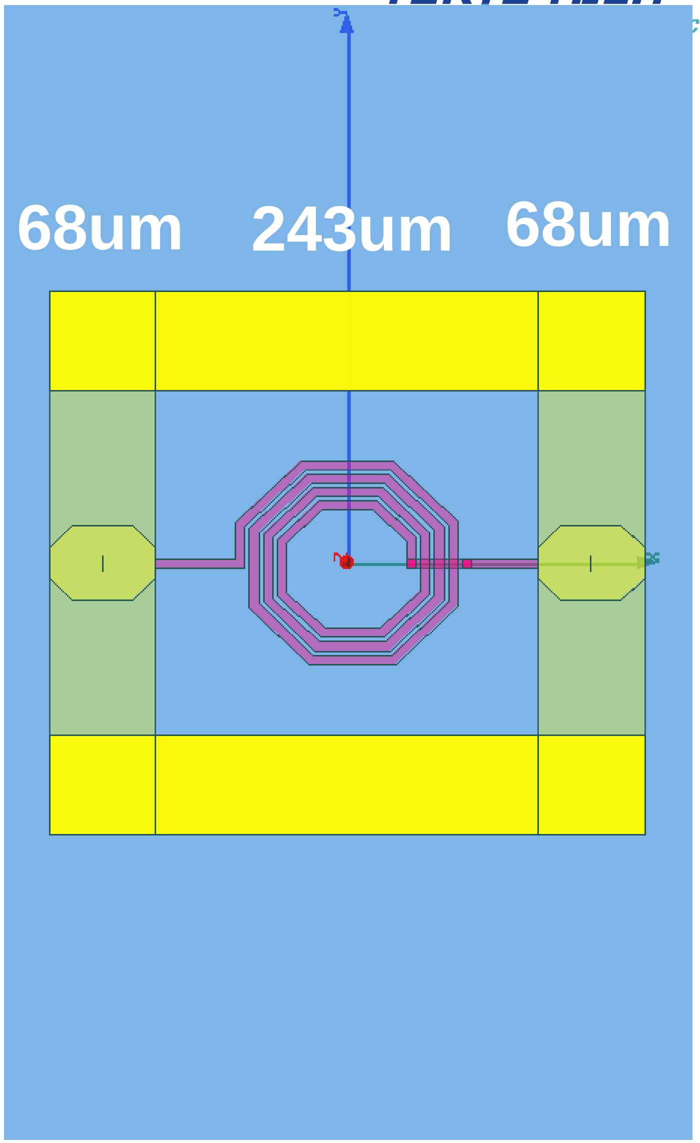
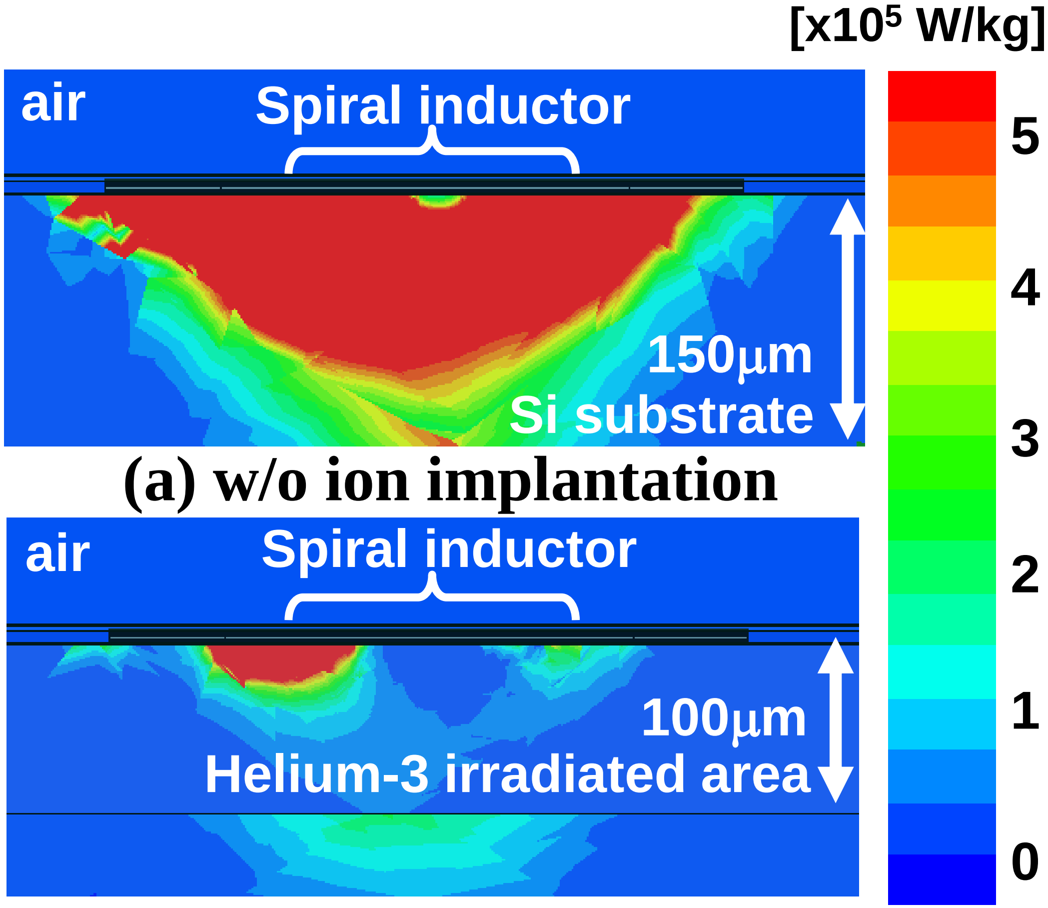
# Inductor EM Simulation

- ◆2-nH inductor
- ◆Two-port
- ◆Open de-embedding
- ◆the 100-µm depth Helium-3 bombardment region
- ◆Above 1-kΩ-cm substrate resistivity



# Inductor EM Simulation Results

## ◆Specific absorption rate (SAR)

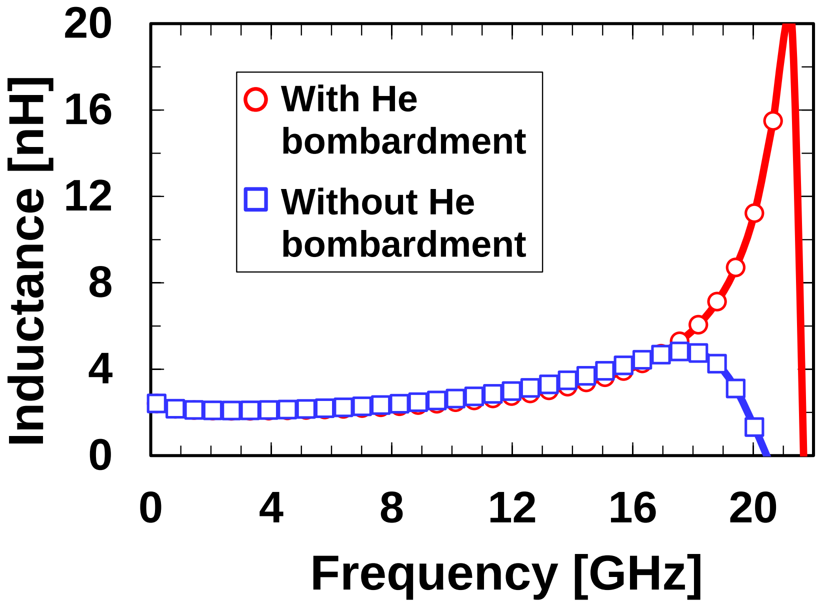


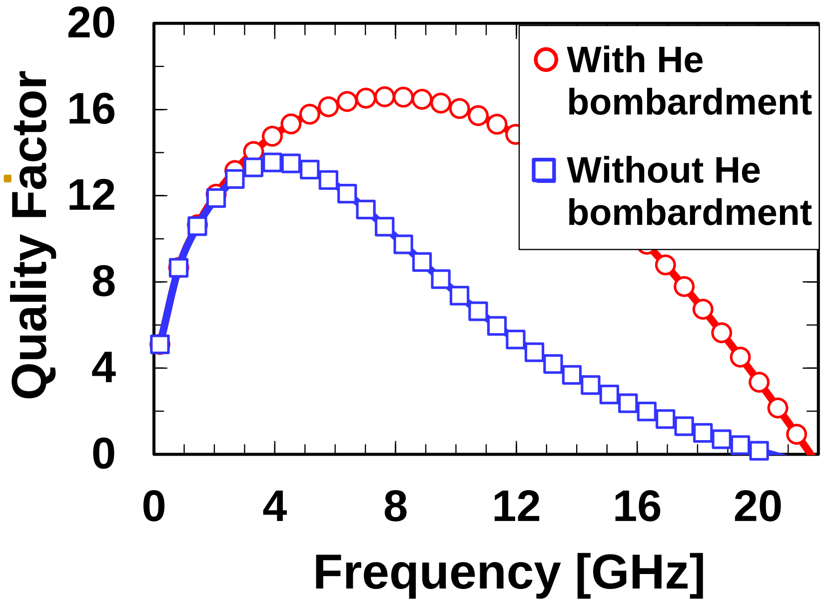
(a) w/o ion implantation

(b) w/ ion implantation

# Inductor EM Simulation Results (Cont'd)

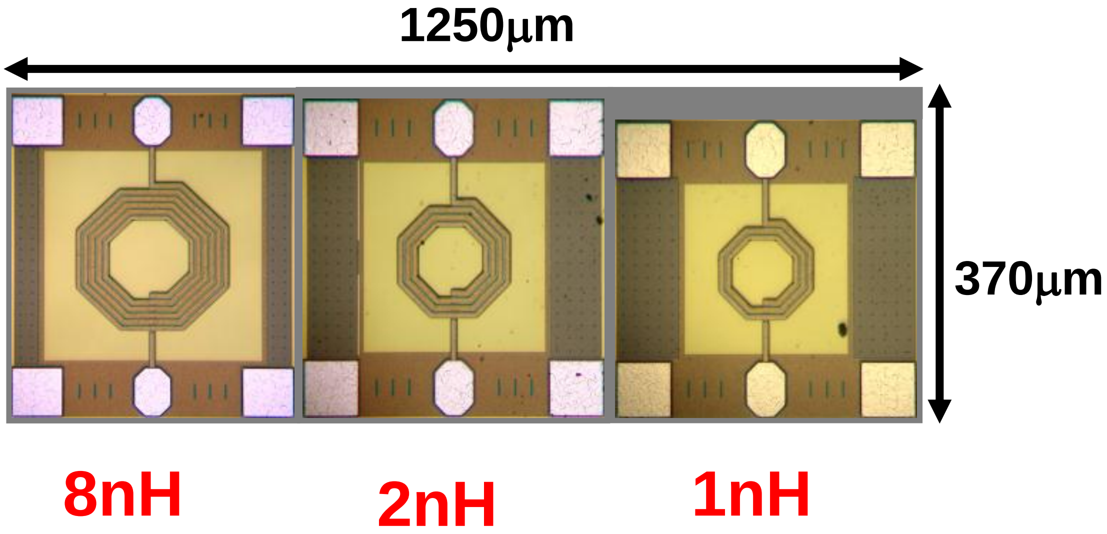
◆ $Q_{peak}$ improved by 23% from 13.5 (without bombardment) to 16.1 (with bombardment).



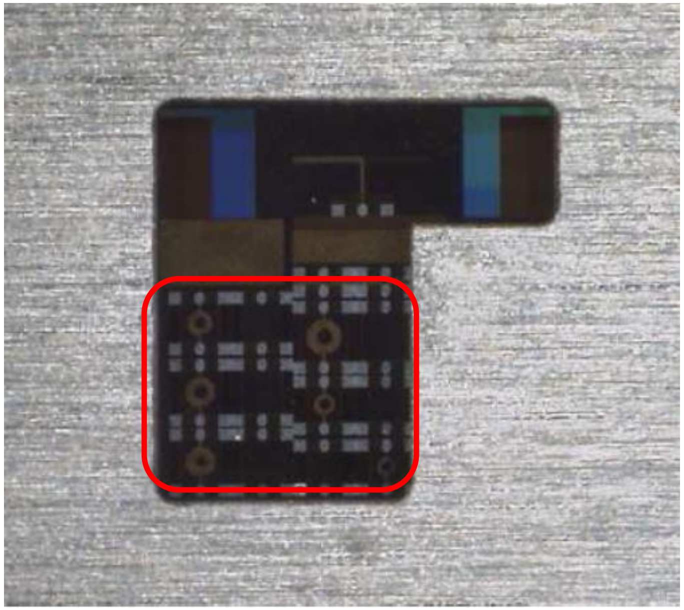


# Inductor Implementation

- 180-nm CMOS process
- 6 metal layers
- Open de-embedding



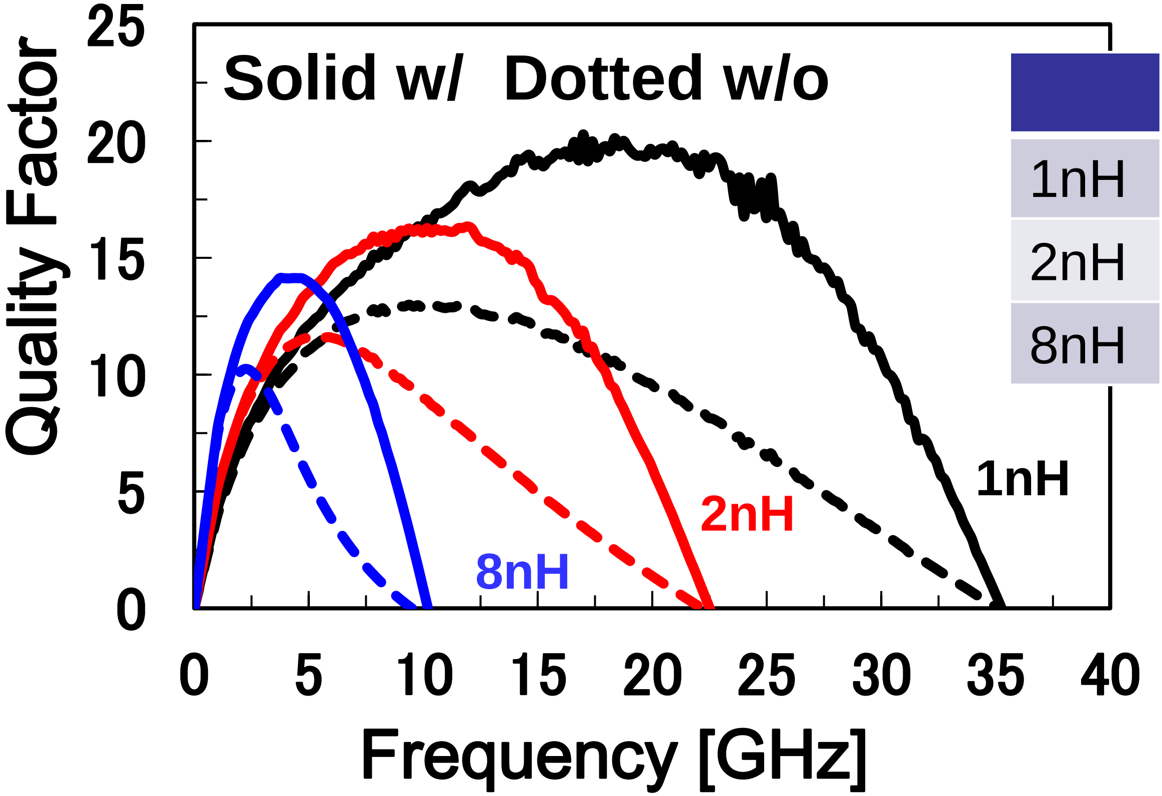
Chip photo



Chip and mask

# Inductor Implementation Results

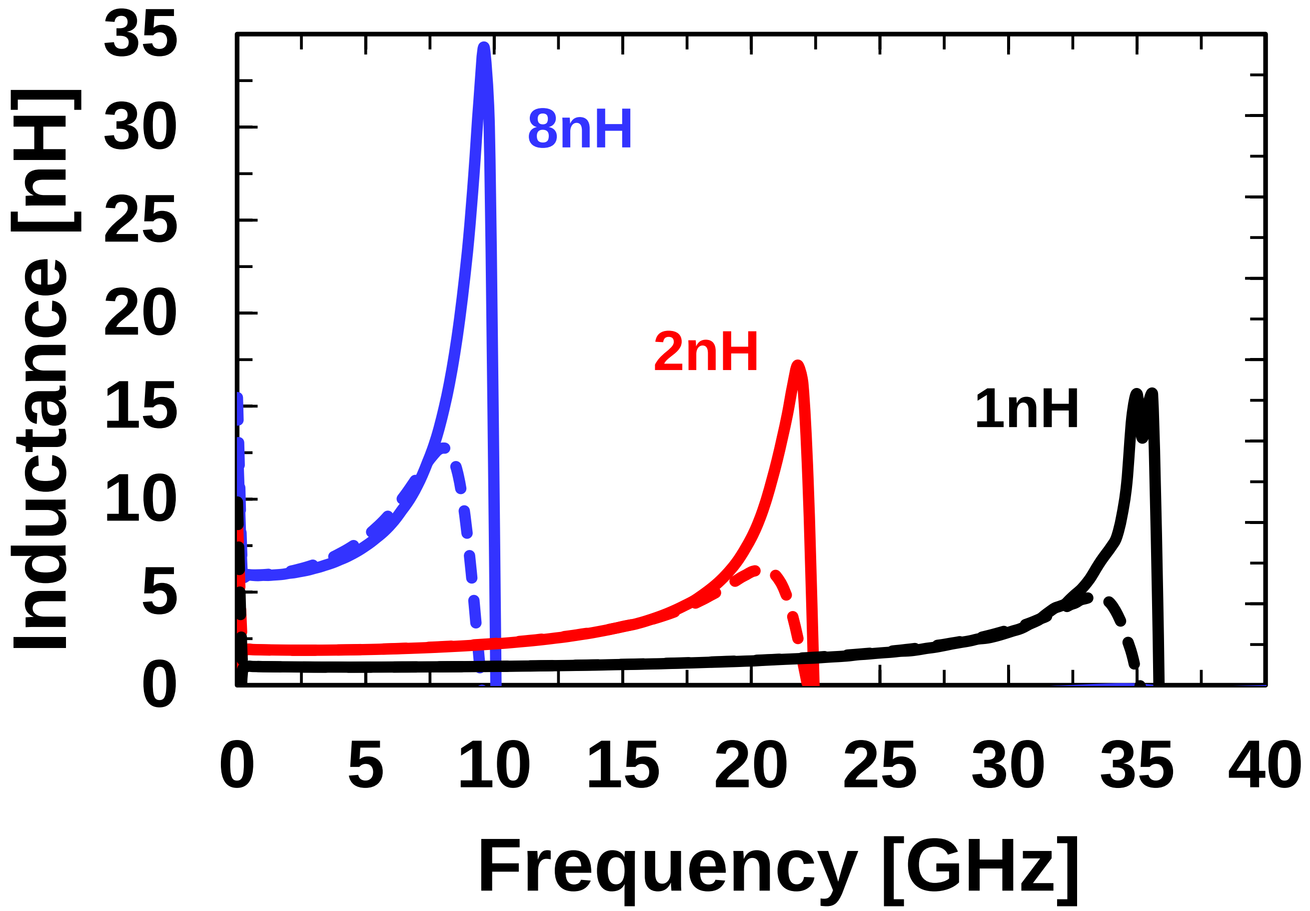
- Q improvement ratios (IR) are 54% for 1-nH inductor.
- Peak shifts to higher frequency while self-resonance frequency does not change.



| | Q(w/o) | Q(w/) | IR(%) |
|---|---|---|---|
| 1nH | 13.0 | 20 | 54% |
| 2nH | 11.6 | 16.3 | 38% |
| 8nH | 10.3 | 14.1 | 36% |

# Inductor Implementation Results (Cont’d)

◆Inductance only has slight change.



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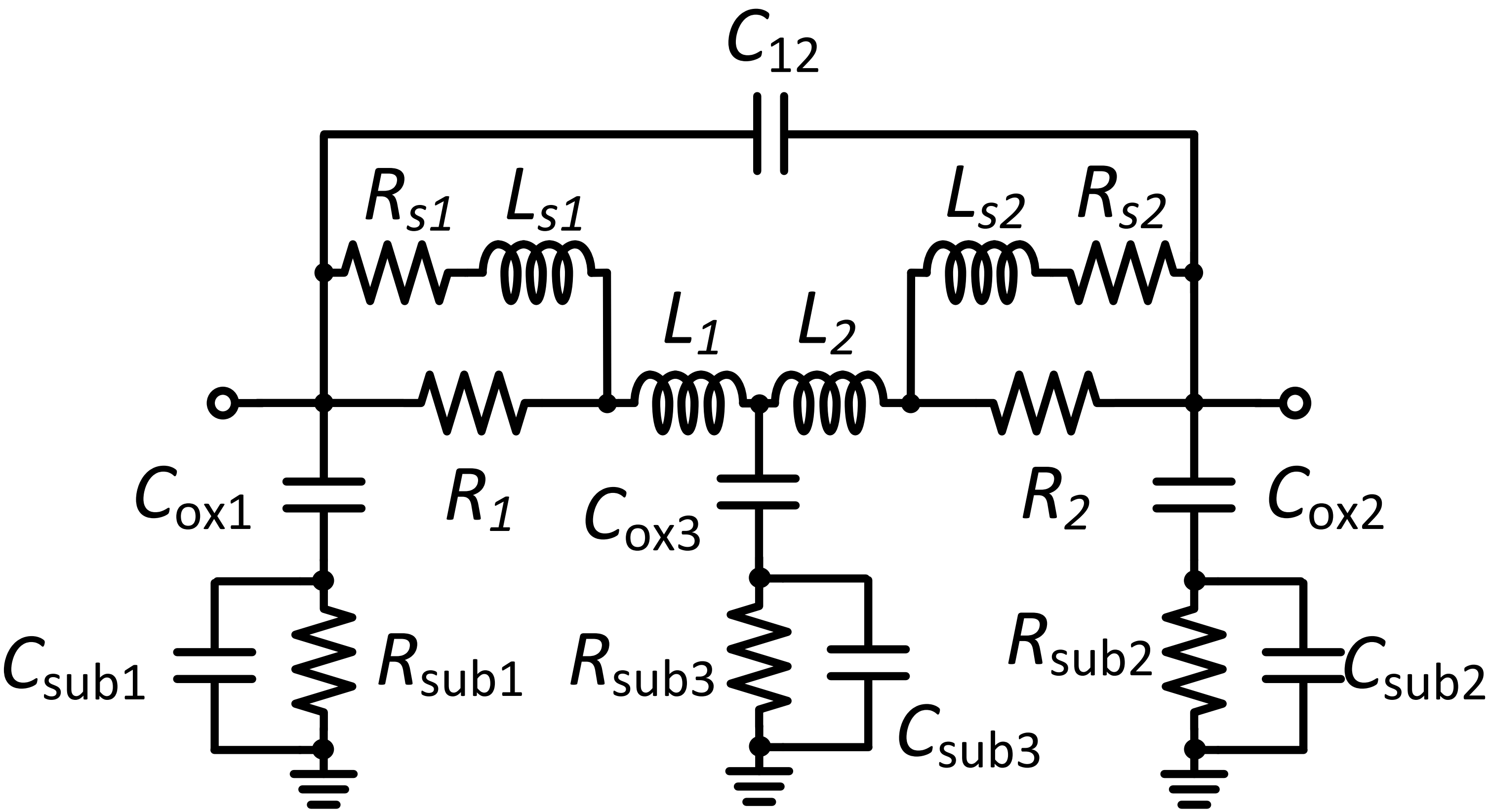
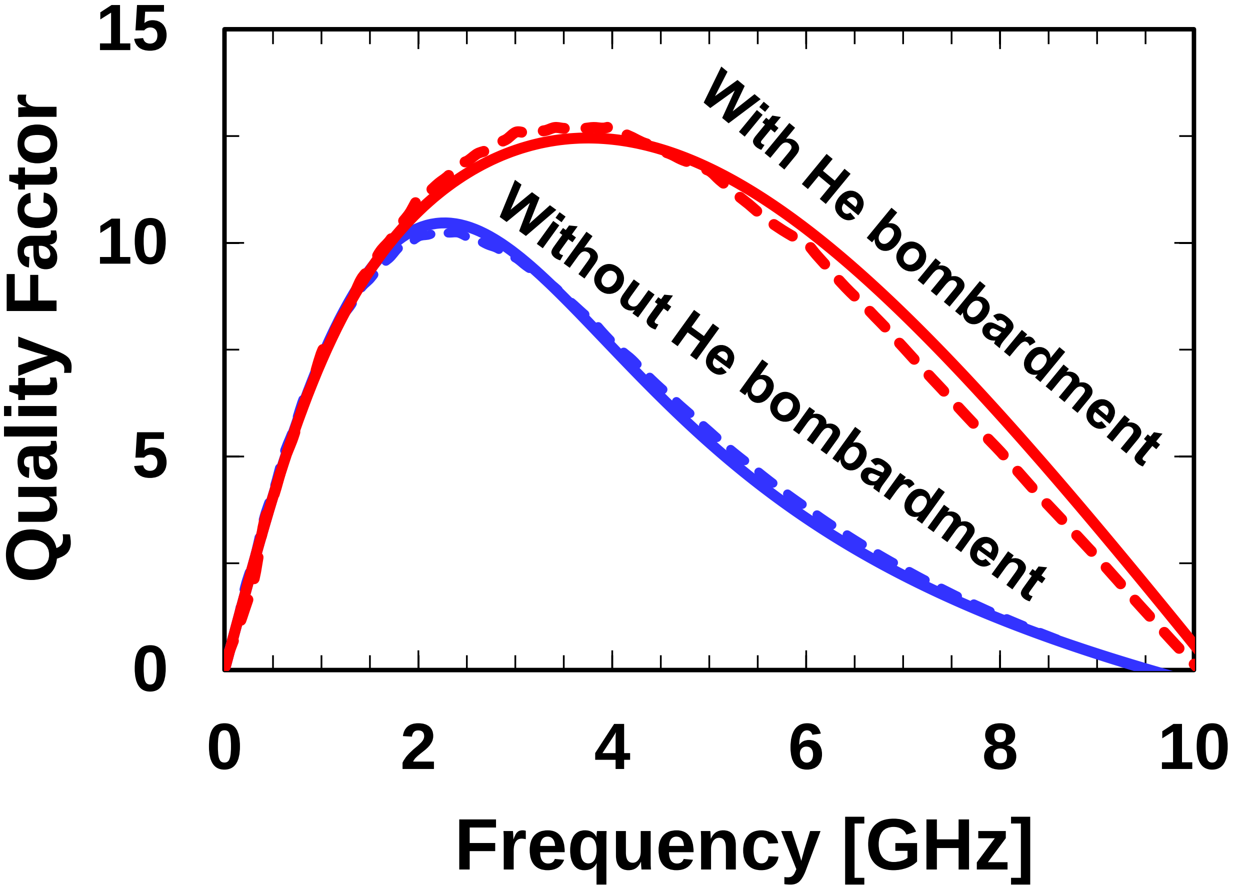
# Inductor Model

- Standard equivalent circuit for easily modeling
- S-parameter fitting



# Inductor Model (Cont'd)

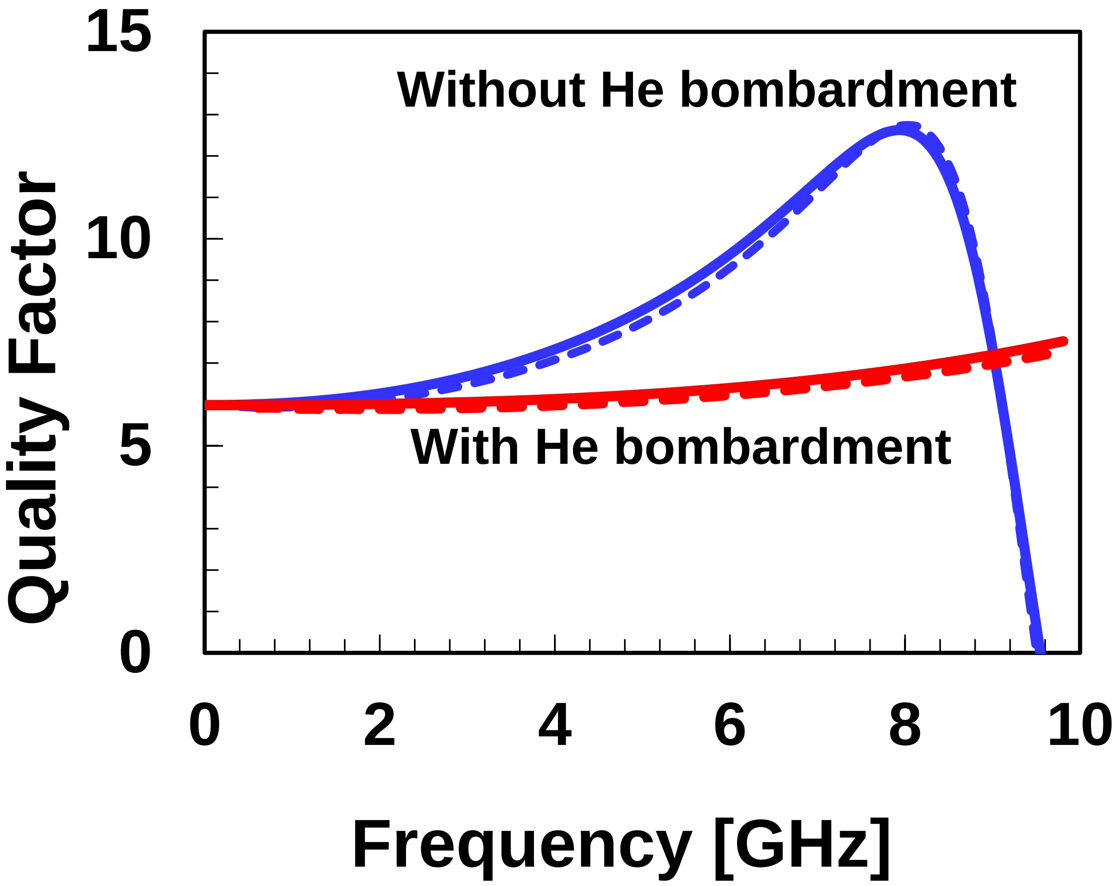
◆Good match for Q is realized.



**Solid lines: model**
**Dash lines: meas.**

# Inductor Model (Cont'd)

- Good match for inductance is realized.



Solid lines: model
Dash lines: meas.

# Extracted Parameters

**Substrate resistances ($R_{sub1}$, $R_{sub2}$ and $R_{sub3}$) are adjusted for characterizing the quality factor difference.**

| Parameter | Without He bombardment | With He bombardment |
|---|---|---|
| $L_1$, $L_2$ [nH] | 2.87 | |
| $R_1$, $R_2$ [Ω] | 4.19 | |
| $L_1$, $L_2$ [nH] | 0.56 | |
| $R_1$, $R_2$ [Ω] | 4.73 | |
| $C_{12}$ [fF] | 36.40 | |
| $C_{ox1}$ [fF] | 23.40 | |
| $C_{ox2}$ [fF] | 24.10 | |
| $C_{ox3}$ [fF] | 47.50 | |
| $R_{sub1}$ [Ω] | $1.00 \times 10^3$ | $7.60 \times 10^3$ |
| $R_{sub2}$ [Ω] | $3.04 \times 10^3$ | $16.50 \times 10^3$ |
| $R_{sub3}$ [Ω] | $0.75 \times 10^3$ | $5.21 \times 10^3$ |
| $C_{sub1}$ [fF] | 5.00 | |
| $C_{sub2}$ [fF] | 2.12 | |
| $C_{sub3}$ [fF] | 7.12 | |

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# Conclusions

- Helium-3 bombardment is proposed to create a local semi-insulated substrate of high resistibility.

- Required dose is about $1.0\text{x}10^{13}\text{cm}^{-2}$, 100 times smaller than the conventional proton bombardment

- Q can be improved by 58% for a 1-nH Inductor.

- Accurate models are realized.

# Acknowledgements

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# Thank you for your attention