Scaling Effect on Specific Contact Resistivity in Nano-scale Metal-Semiconductor Contacts

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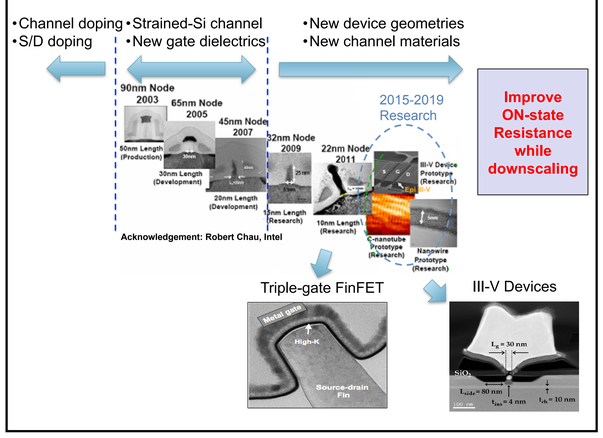
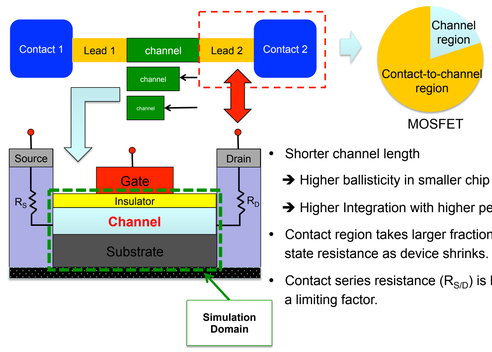
Towards Contact Resistance Modeling

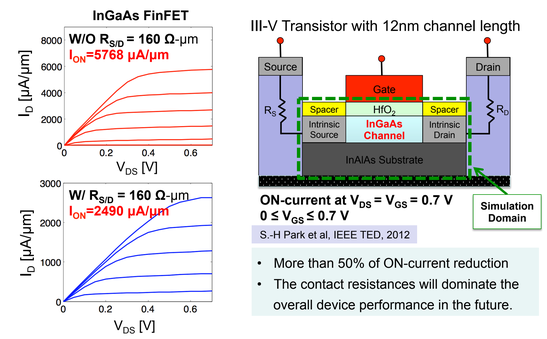


Importance of Contact Resistance



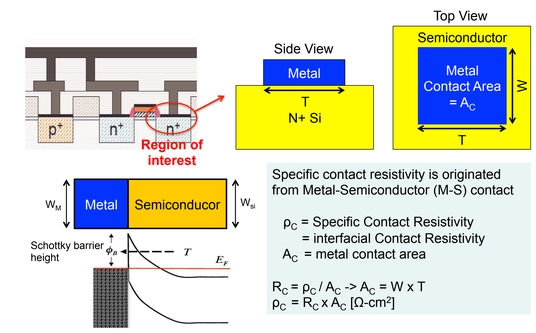
- Shorter channel length
  - ➔ Higher ballisticity in smaller chip
  - ➔ Higher Integration with higher perfom.
- Contact region takes larger fraction of on-state resistance as device shrinks.
- Contact series resistance ($R_{S/D}$) is becoming a limiting factor.

Impact of Contact Resistance



- More than 50% of ON-current reduction
- The contact resistances will dominate the overall device performance in the future.

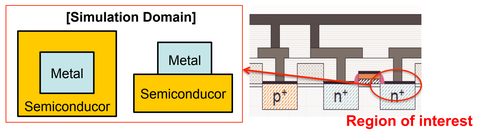
Specific Contact Resistvity 101



Objective and Modeling Approach

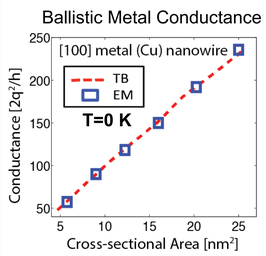
Objective

- Impact of interface area scaling as device shrinks is questionable.
- Significant increase of contact resistivity is observed when the metal-semiconductor junction area reaches to the certain limit (sub-10nm).



INPUTS	SIMULATION	OUTPUT
Contact area, Schottky barrier height, doping concentration	2-D / 3-D NEGF Poisson Solver: Effective Mass Approximation due to large size	Calculate the contact resistivity from quantum transport simulation

TB Fitting Model for Metal Wire Conductance

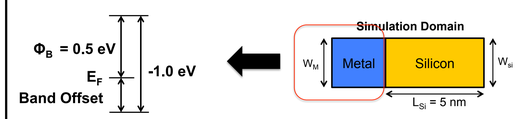


- Tight-binding method is employed for an accurate full quantum mechanical description of the electronic structure of pure metal.
- Fit the metal wire conductance from effective mass with TB results

[1] N. Kharche et al, 'Orientation-Dependent Ballistic Transport in Nano-scale Copper and Aluminum Wires', unpublished
[2] G. Hegde et al, 'Effect of transport orientation and quantum confinement on the conductance of copper – a computational study'

As the conductance of metal wire decreases LINEARLY while downscaling, the resistivity becomes almost CONSTANT

Metal-Si Contact Modeling in EM



- Pull down bands below E_F in Metal
- Provide enough electrons (carriers)
  → **Metal-like-behavior**
- High dielectric constant
  → **strong screening**

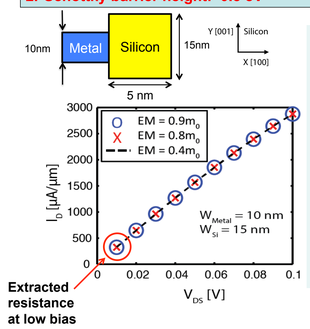
1. **Doping concentration in silicon: N_D=1e20 - 2e20 /cm³**
2. **Schottky barrier height: 0 eV – 0.5 eV**

Ref. [1] Neerav Kharche et al., IEEE TED, 58, 7 (2011)
Ref. [2] Qun Gao et al., JAP 109, 104307 (2011)
Ref. [3] Qun Gao et al., JAP 111, 104305 (2011)

	Multi-Valley Effective Mass Model	Dielectric Constant
Silicon	Standard effective mass	11.7
Metal	TB fitted effective masses (m_t = 0.4m0, m_l = 0.15-0.1m0)	1000

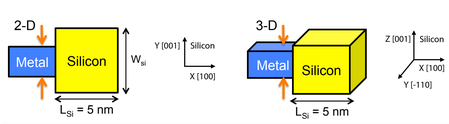
Low field I-V Linearity of M-Si Contact Model

1. **Doping concentration in silicon: N_D=2e20 /cm³**
2. **Schottky barrier height: 0.5 eV**

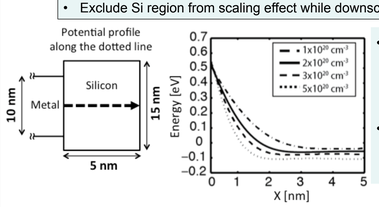


- Tested with three different metal effective masses
  -> m_t= 0.9 m0, 0.8 m0, and 0.4 m0.
- Applied bias (V_{DS}) = 0.01 – 0.1 V
- Shows exactly same linearity in I-V characteristics.
- This is because: when two materials are connected in series, the system conductance depends on the conductor which has lower conductance (Si Contact Pad).

Doping Effect in Si Contact Pad

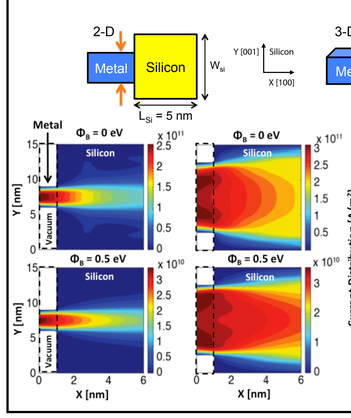


- Highly doped Si contact pad is used, and [100] transport direction.
- Fixed W_{Si}=15 nm in 2-D and A_{Si}=10x10 nm² in 3-D (avoid non-parabolicity)
- Exclude Si region from scaling effect while downscaling contact region.



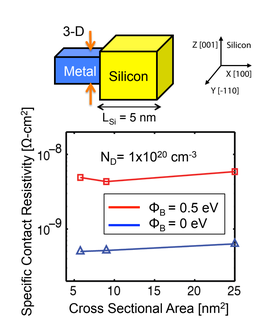
- Schottky barrier gets thinner as doping concentration increases in the simulation model
- Doping concentration in contact pad varied from 1e20 to 5e20 cm⁻³

Schottky Barrier Height between M-Si Contact



- Transport resolves spatial current spreading at contact and in Si
- Increased Schottky barrier height reduces current density (one order of magnitude for 0.5eV)
- Barrier height can be varied through alloy magic

Metal Interconnect Scaling Effect



- Lower Schottky barrier indeed provide lower resistivity.
- **Contact resistivity is almost constant while downscaling cross sectional area of metal interconnect.**
- Metal conductance decreases linearly as while downscaling.
- No scaling effect is found within the ballistic transport regime in M-Si structure.

Summary and Conclusion

- Contact resistance is becoming a critical factor in on-state performance of devices
- Industry is in need of quantitative nano-scaled contact models
- Mode mismatch plays a role at the nano-scale
  - Back to the 80's - but now in SI and metals and at room temperature.
- Simple effective mass model calibrated against more complex DFT/ tight-binding DOS
  - Modeled simple 2-D / 3-D M-Si junction structure
  - Fit ballistic conductance of pure metal (Cu) wire in EM with TB
- Conclusion
  - Contact resistivity is almost constant while downscaling cross sectional area of metal interconnect.
  - Surface roughness of metal wire and grain boundary distribution are expected to cause the conductivity degradation.