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Photo-excited hot electrons from conductive films forming heterojunctions

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Akira Otomo[3] and Tadaaki Nagao [1,2]

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[2] Core Research for Evolutional Science and Technology (CREST), Japan Science and Technology Agency (JST), Japan
[3] Advanced ICT Research Institute, National Institute of Information and Communications Technology (NICT), Japan

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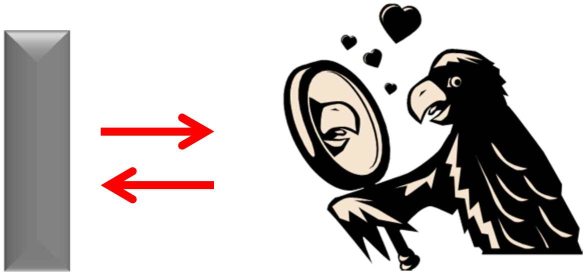
- Introduction
  - – Hot electron excitation from metals
- Photodetectors for optical waveguides
- Transparent photodetectors with oxides
- Summary

References

- Japanese patent: Application number (2014) 39325
- S. Ishii, et al, under review (2014)

Optical properties of metals

- Metals
  - Reflect light
    - No transmission
  - Complex permittivities

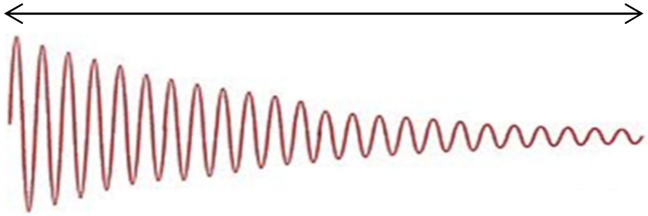


Metallic surface

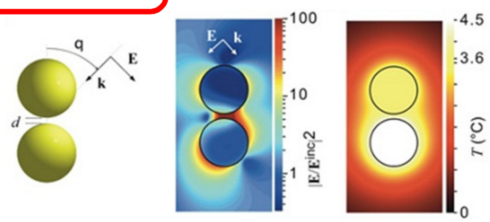
$$\varepsilon(\omega) = \varepsilon'(\omega) + i\varepsilon''(\omega)$$

ε ‘ < 0 losses

Surface plasmon polaritons (SPPs)
Propagation length : ~mm



- Hot electrons
- Heat



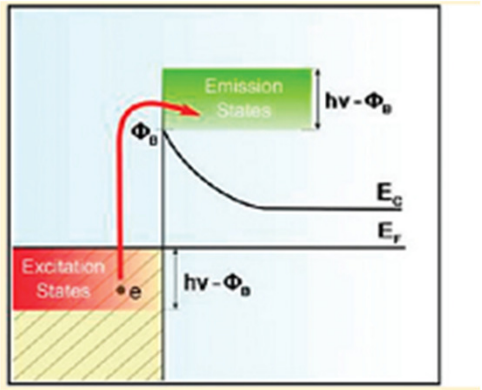
G. Baffou, et al, ACS Nano (2010)

  - Thermo-plasmonics

Metallic photodetectors

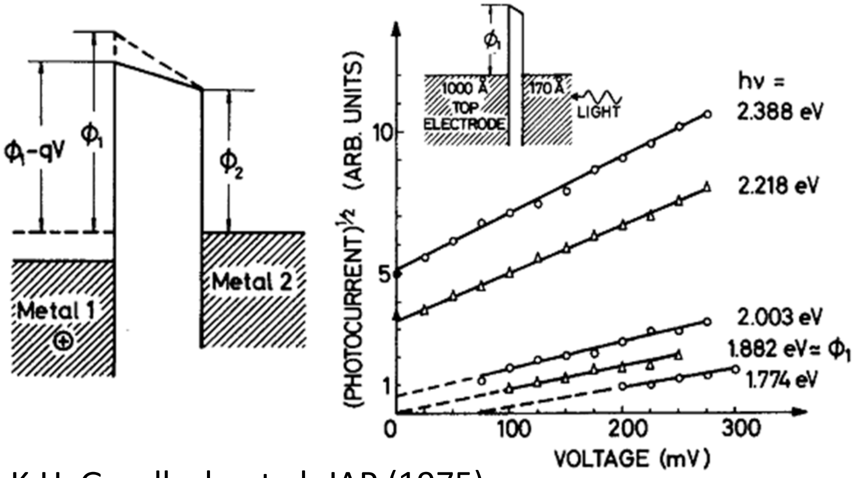
Absorption in metals = generation of hot electrons

- Schottky contacts
  - Metal-semiconductor contacts
    - e.g. Au-Si
  - Internal photoemission from metal
    - (photon energy) < (bandgap)



I. Goykhman, Nano Lett. (2011)

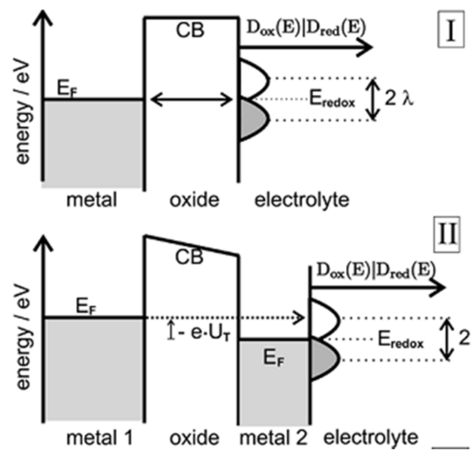
- MIM structures
  - Metal-insulator-metal (MIM) with thin films
  - Photocurrent by the hot carriers crossing the insulator barrier
    - (photon energy) < (bandgap)



K.H. Gundlach, et al, JAP (1975)

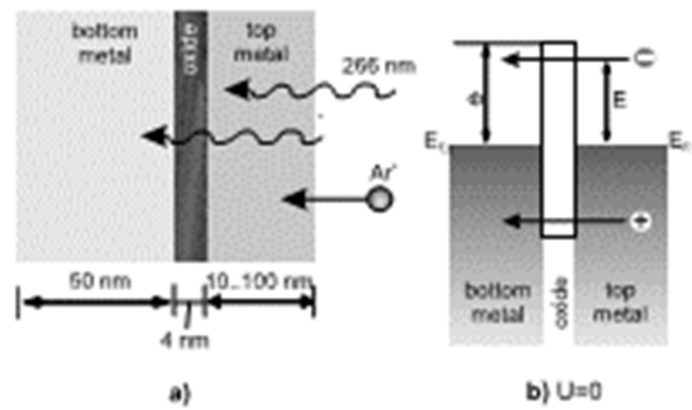
Recent studies using MIM structures

Electrochemical surface science



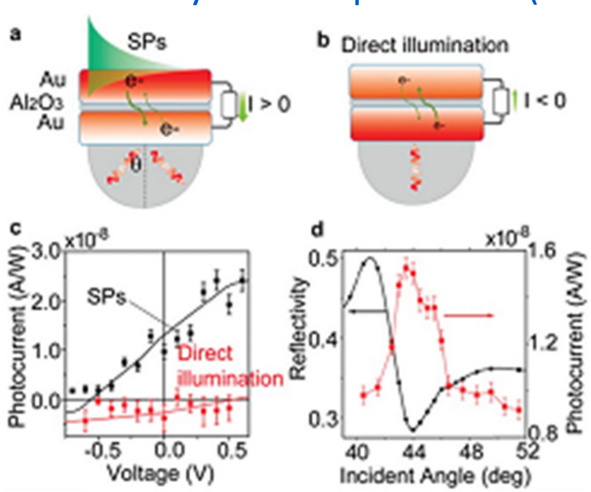
D. Diesing, et al, J Solid State Electrochem. (2003)

Excitation by photons & particles



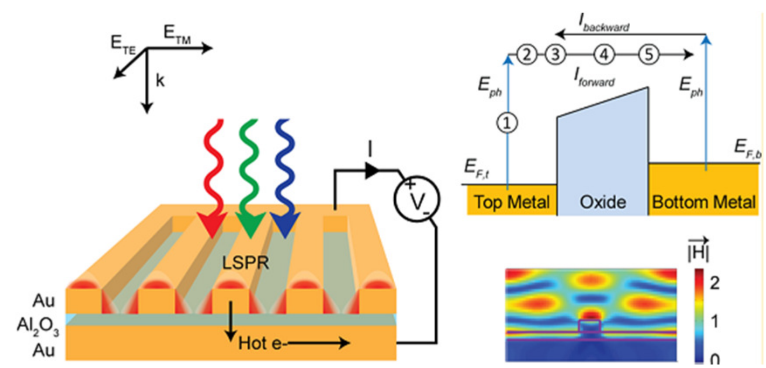
Kovacs, et al, PRB (2007)

Excitation by surface plasmons (SPs)



F. Wang and N.A. Melosh, Nano Lett. (2011)

Plasmonic resonances



H.Chalabi, et al, Nano Lett. (2014)

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- **Photodetectors for optical waveguides**
- Transparent photodetectors with oxides
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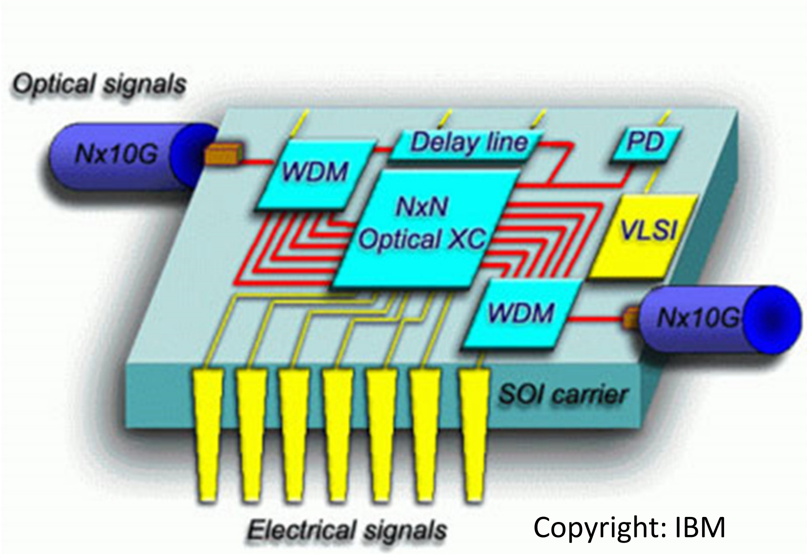
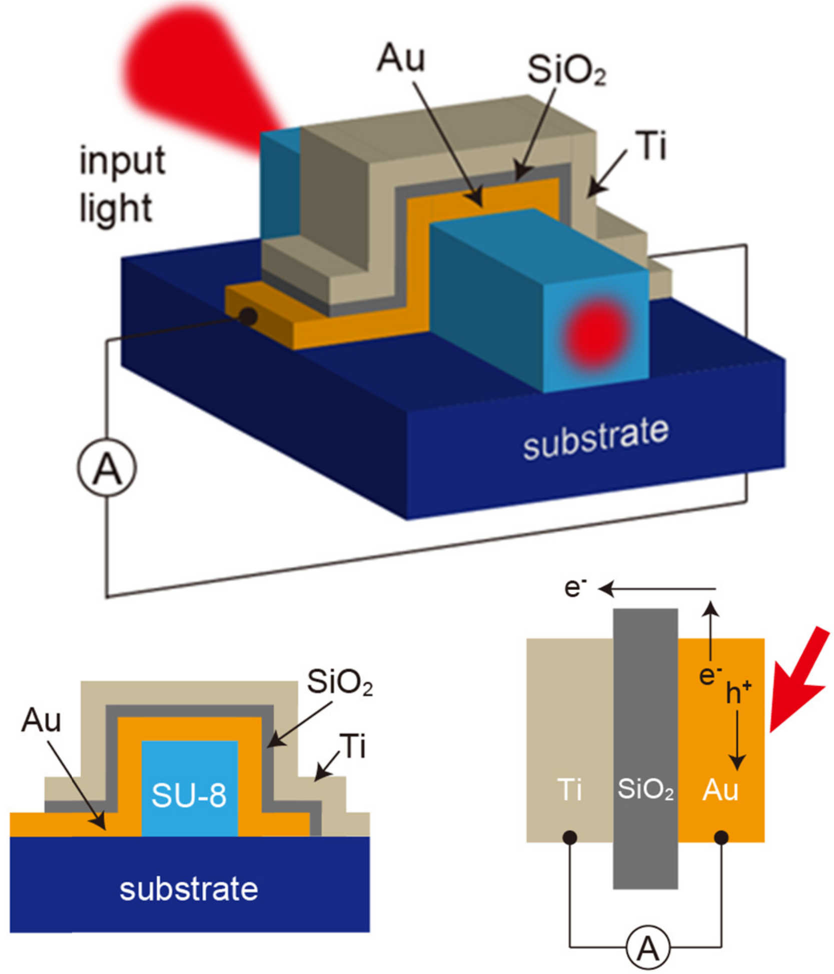
- S. Ishii, et al, under review (2014)

MIM photodetector for optical waveguides

Metals are everywhere on opto-electronic chips

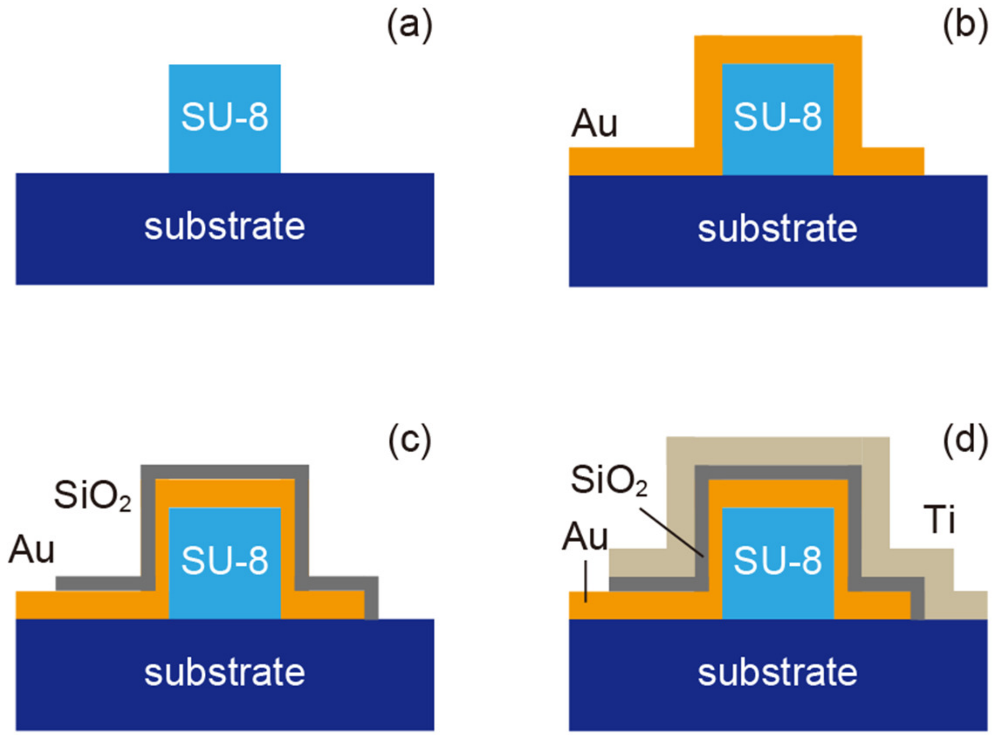




Ishii and Inoue, patent application (2014)

Hot electrons excited in metal films by the evanescent field of guided light

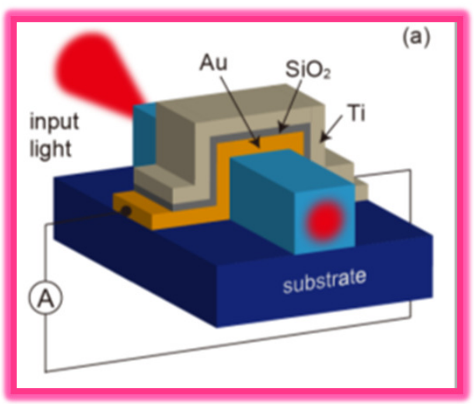
Device fabrication

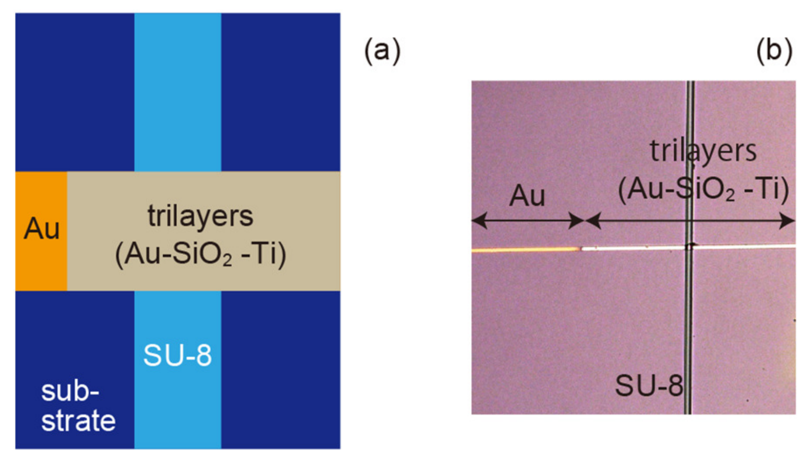


SU-8 waveguide:
- Height: 1.53 µm
- Ave. width: 6.5 µm

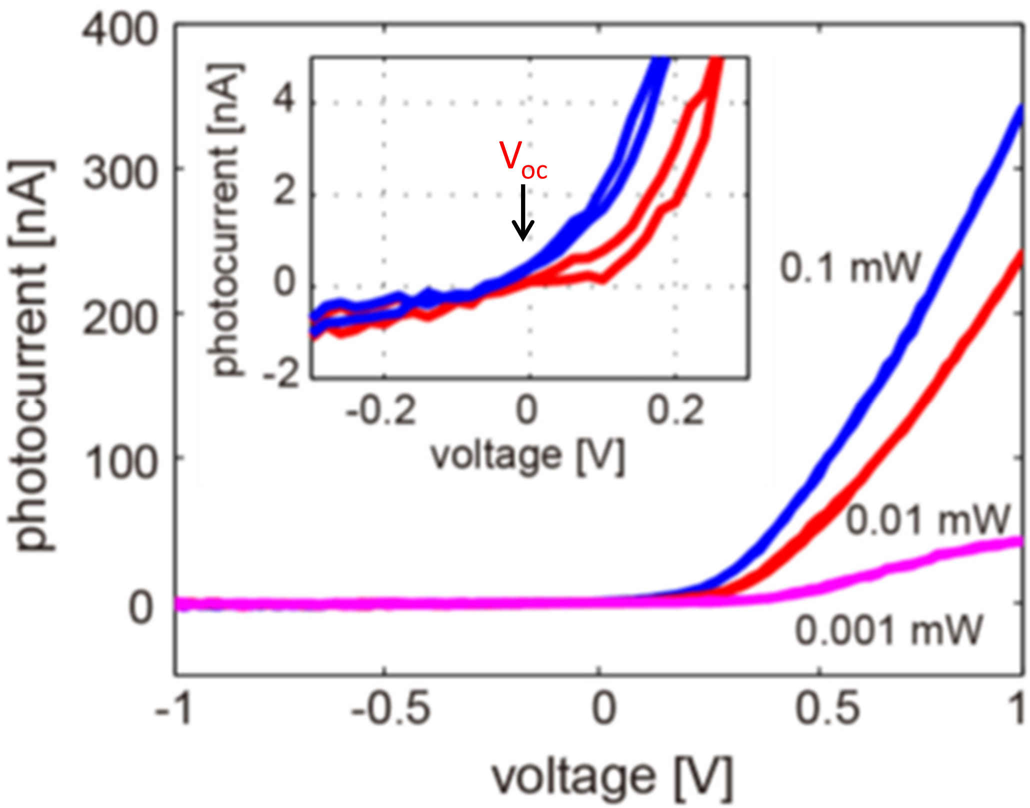
Film thicknesses:
- Top (Ti): 25 nm
- Middle (SiO_2): 10 nm
- Bottom (Au): 20 nm

Film widths: 5 µm

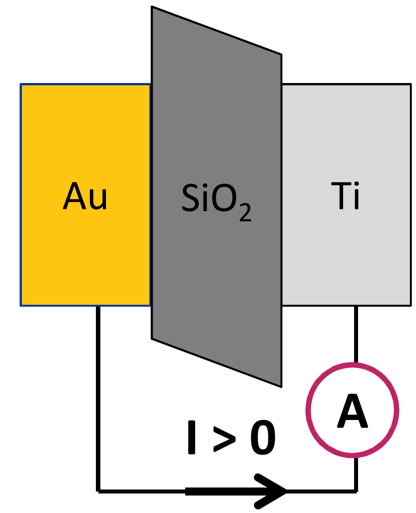




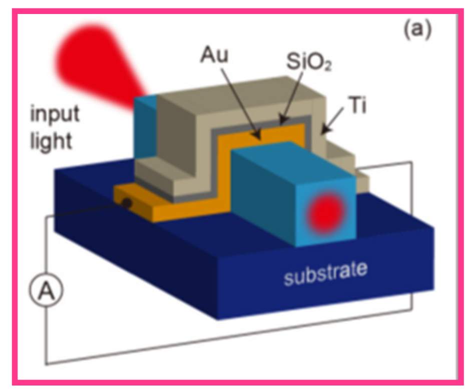
Photodetection



- Input wavelength: λ = 680 nm

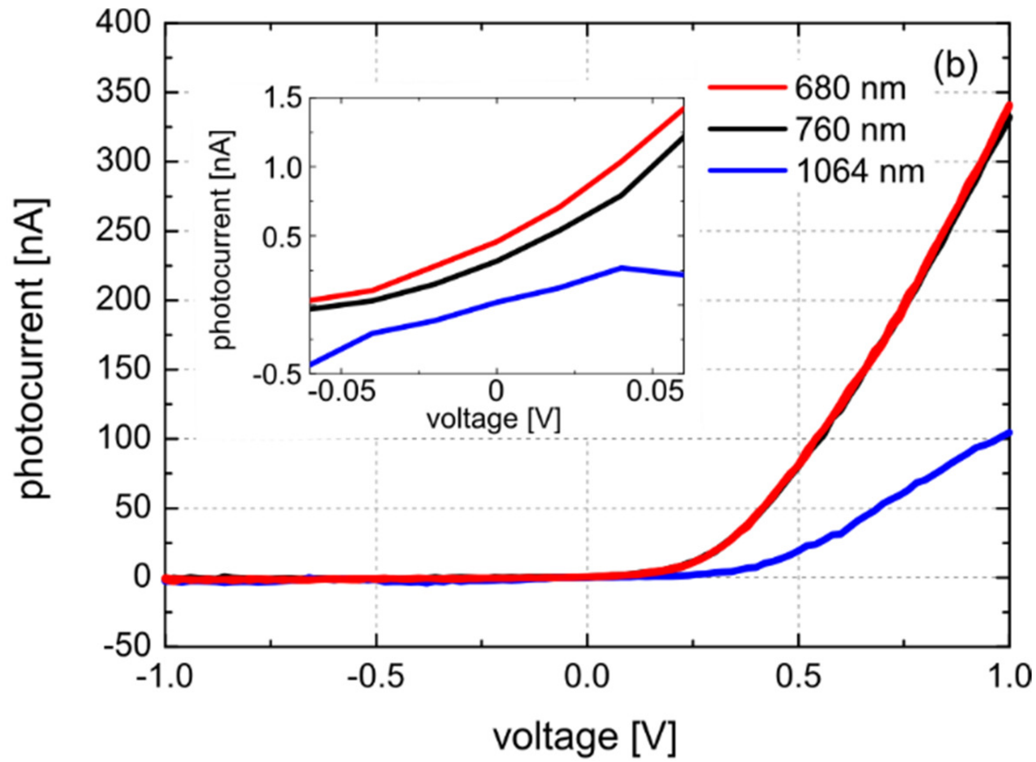


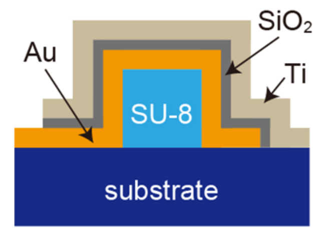
- Photocurrent generation by the guided light
- Positive bias↑ => photocurrent ↑
- Open circuit voltage (V_{oc}) = -0.05 V



Wavelength dependence

- Input power: 0.1 mW
- Wavelength: 680, 760 & 1064 nm

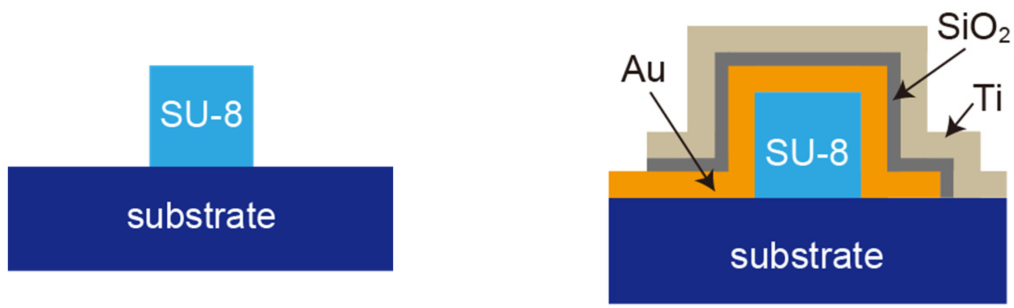




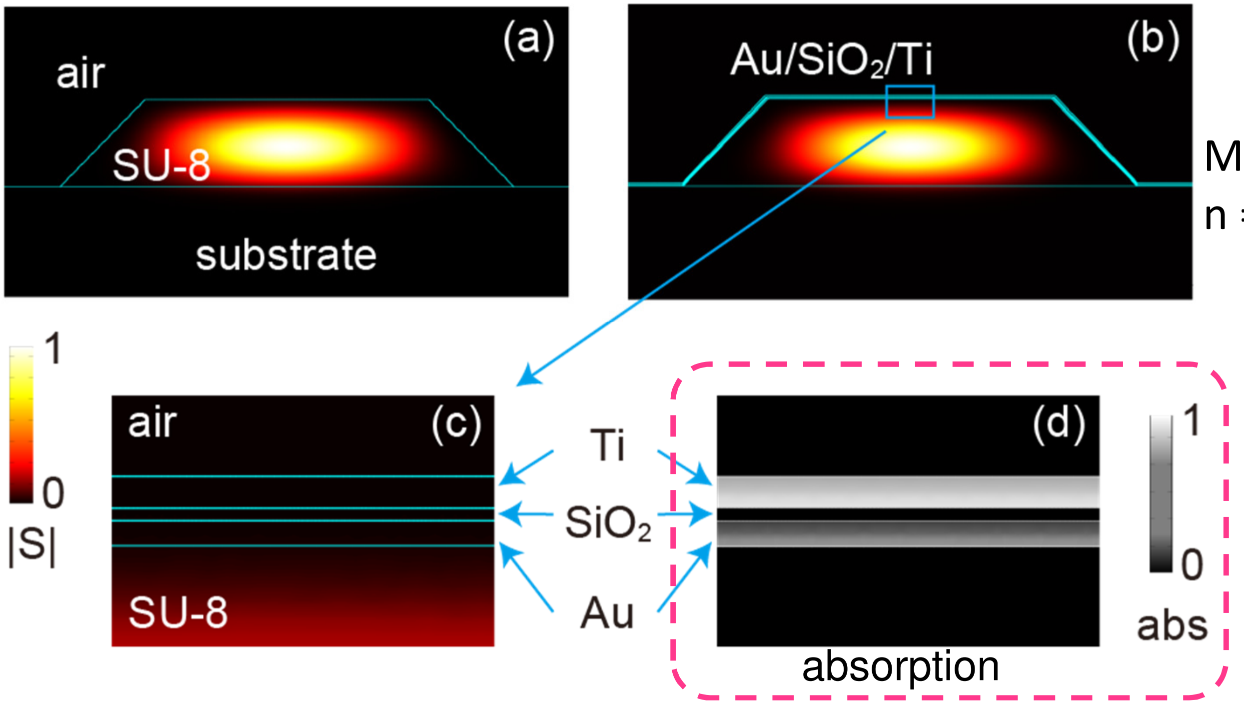
- Photodetection up to λ = 1064 nm
- Higher photocurrent at shorter input wavelength
- Open circuit voltage (V_{oc}) ~ 0

Mode analysis

λ = 680 nm



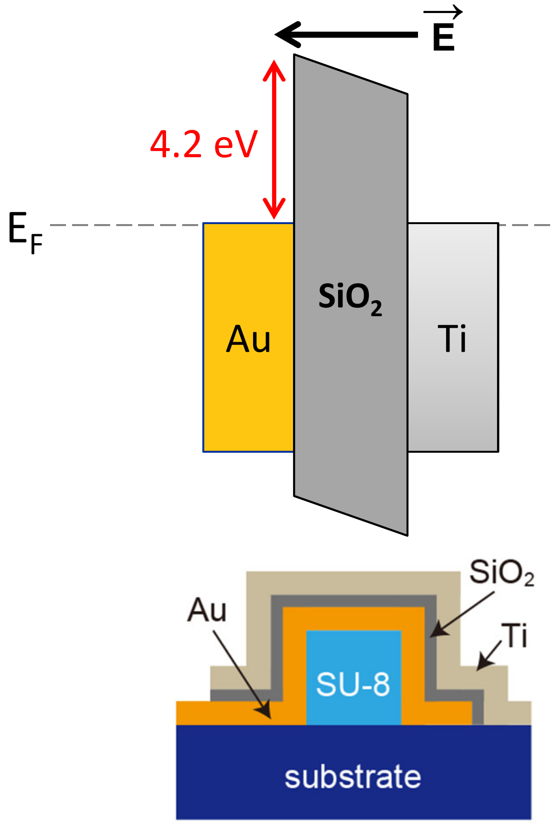
Mode index:
n = 1.5579



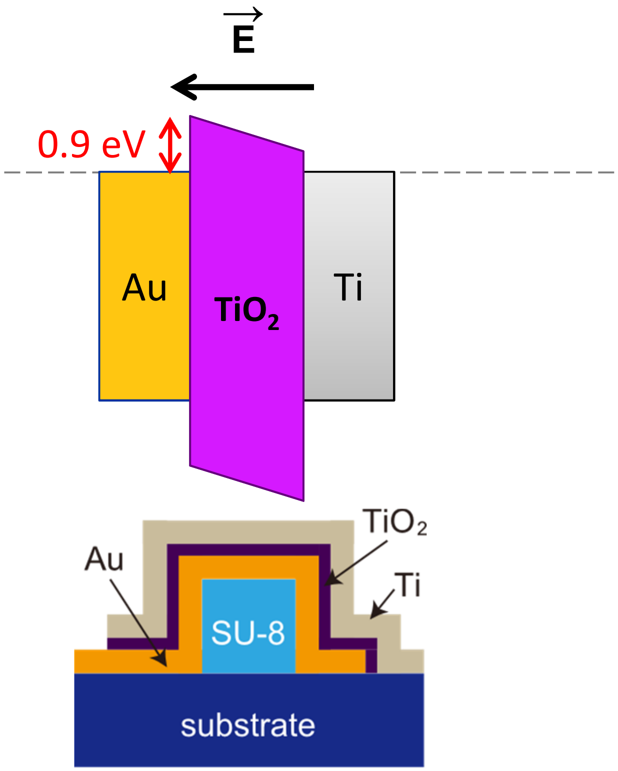
Mode index:
n = 1.5570+i9.3×10^{-5}

Small portion of guided light is absorbed by the metals

Electronic structures of MIMs



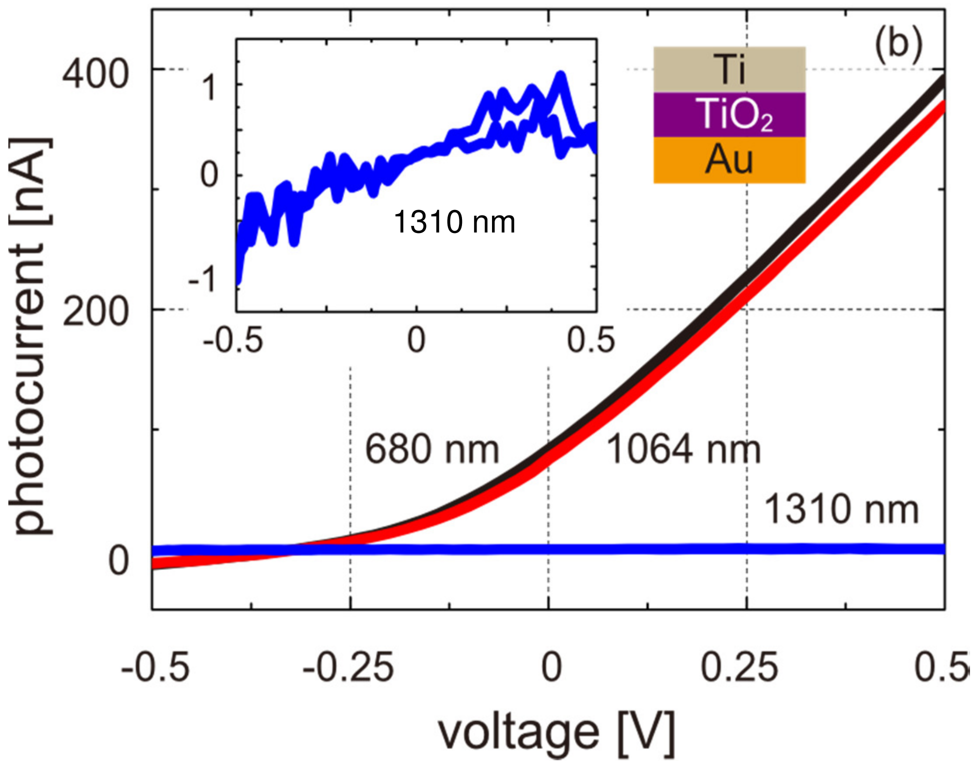
- Au-SiO_2-Ti
  - Barrier height ~ 4 eV
  - Tunneling for visible and NIR
    - Open circuit voltage (V_{oc}) ~ 0

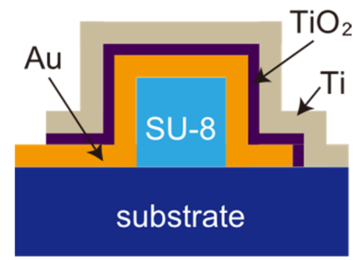


- Au-TiO_2-Ti
  - Barrier height ~ 0.9 eV
  - Open circuit voltage (V_{oc}) for λ < ~1.4 µm
  - Tunneling for λ > ~1.4 µm

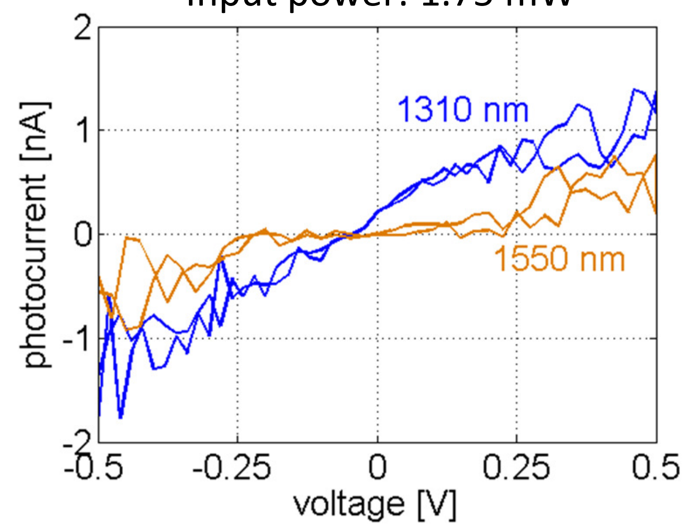
MIM with Au-TiO_2-Ti

Input power: 1.0 mW





Input power: 1.75 mW

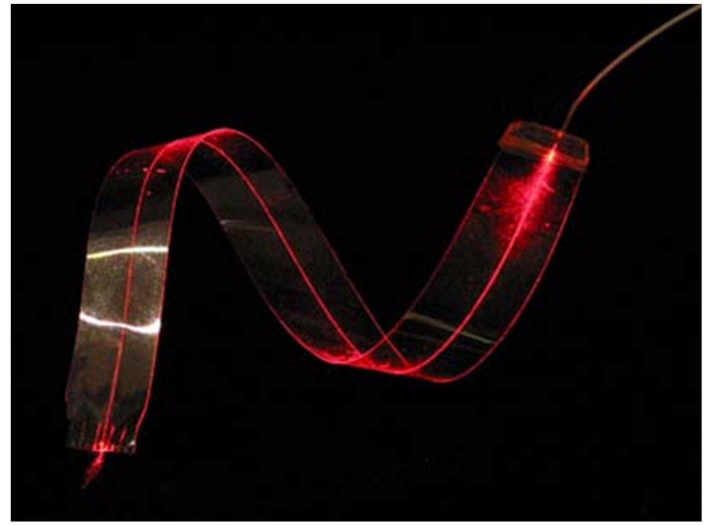


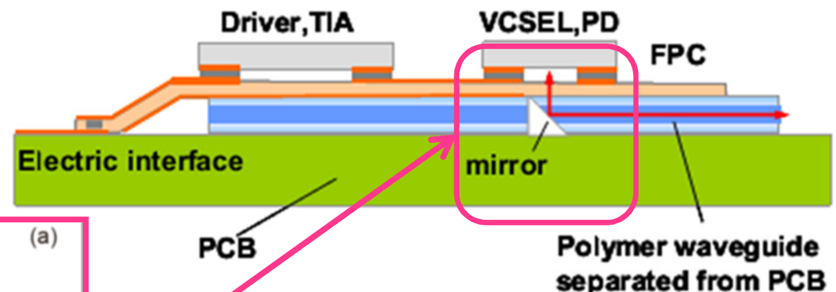
- Photodetection up to λ = 1550 nm
  - λ < ~1400 nm: Open circuit voltage (V_{oc}) < 0
  - λ > ~1400 nm: V_{oc} = ~0 (tunneling)

Where can we use MIM?

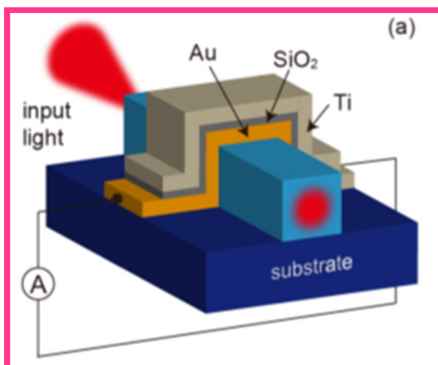
- Silicon photonics
  - Si-Ge photodiodes
  - Schottky contacts
- Ⅲ-Ⅴ photonics (e.g. InP)
  - Ⅲ-Ⅴ photodiodes
- Polymer/dielectric photonics
  - Semiconductor photodiodes

    <= replace with our detectors





Shiraishi, et al, OFC/NFOEC (2011)



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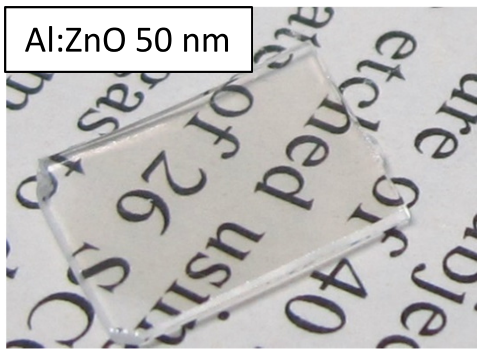
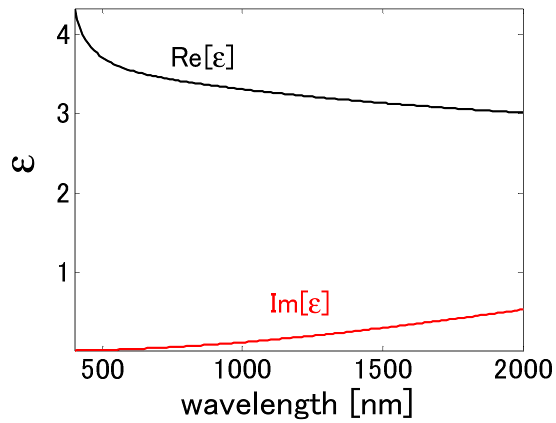
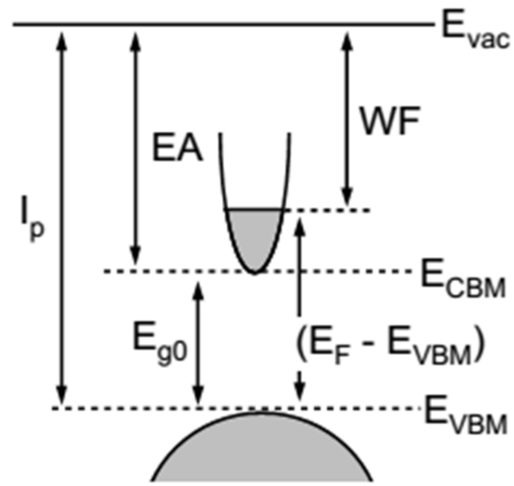
Properties of TCOs

- Transparent conductive oxides (TCOs)
  - High carrier concentrations (< ~10^{-21} cm^{-3})
  - Transparent (if thin)
  - Small light absorption
    - $Im[\varepsilon] > 0$

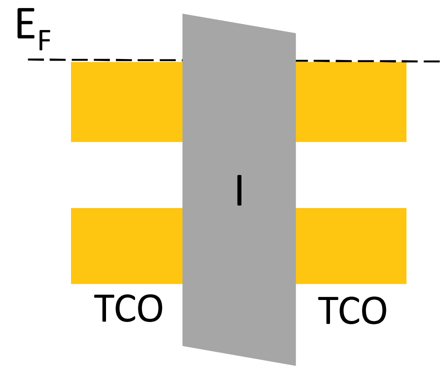




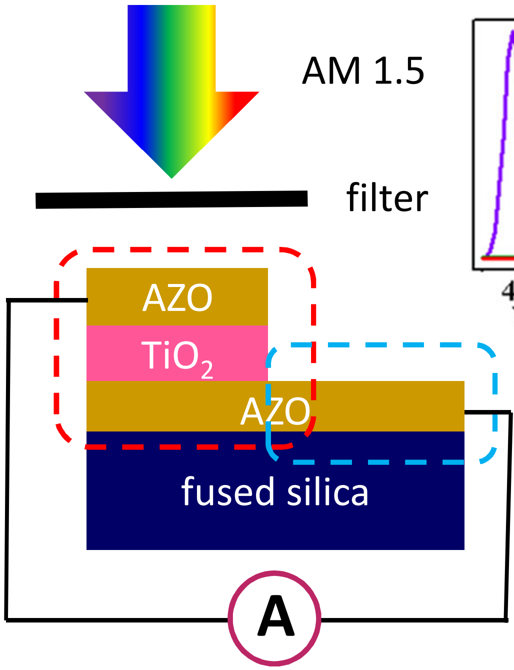


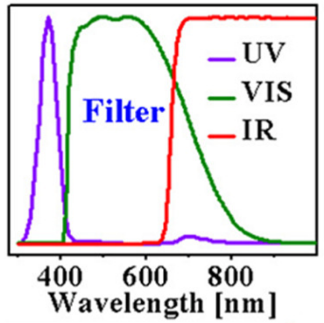
A. Klein, et al, Materials (2010)

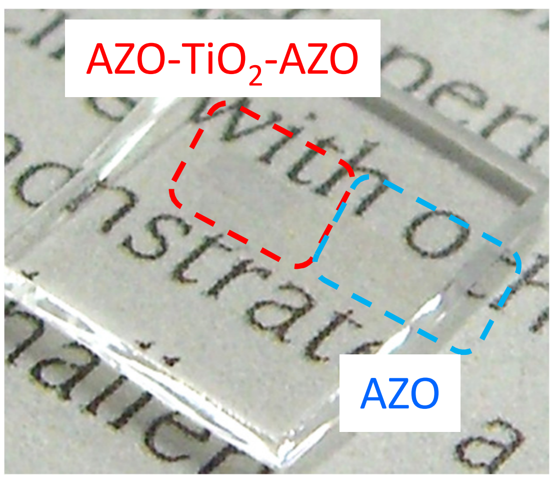
=> Transparent photodetectors with TCO–insulator(I)–TCO structures

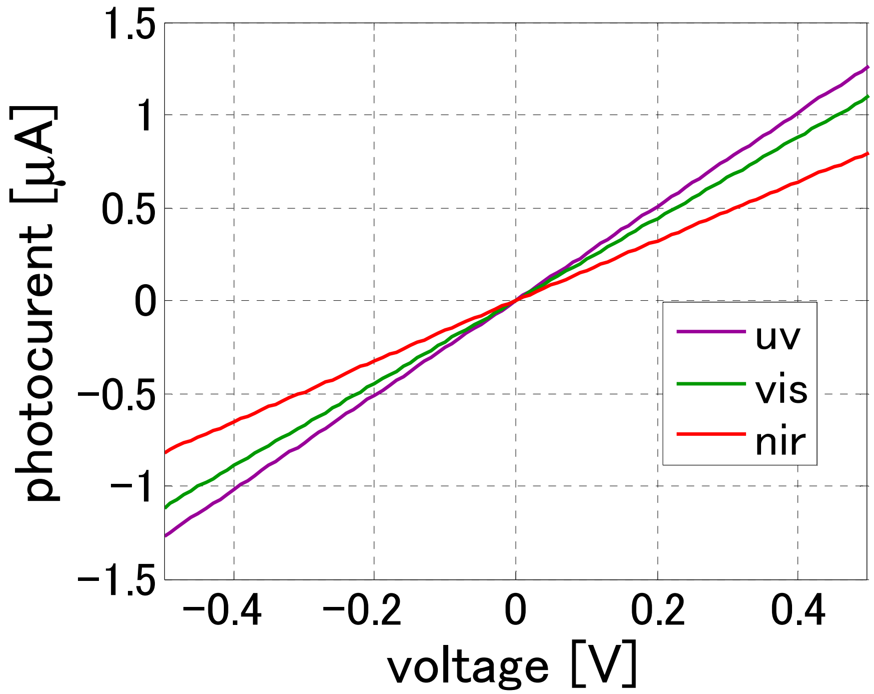


Photodetection with TCOs









- Photodetection in VIS & NIR
  - $E_g(TiO_2)$ = 3.2 eV (λ = 387 nm)
  - No pn junctions

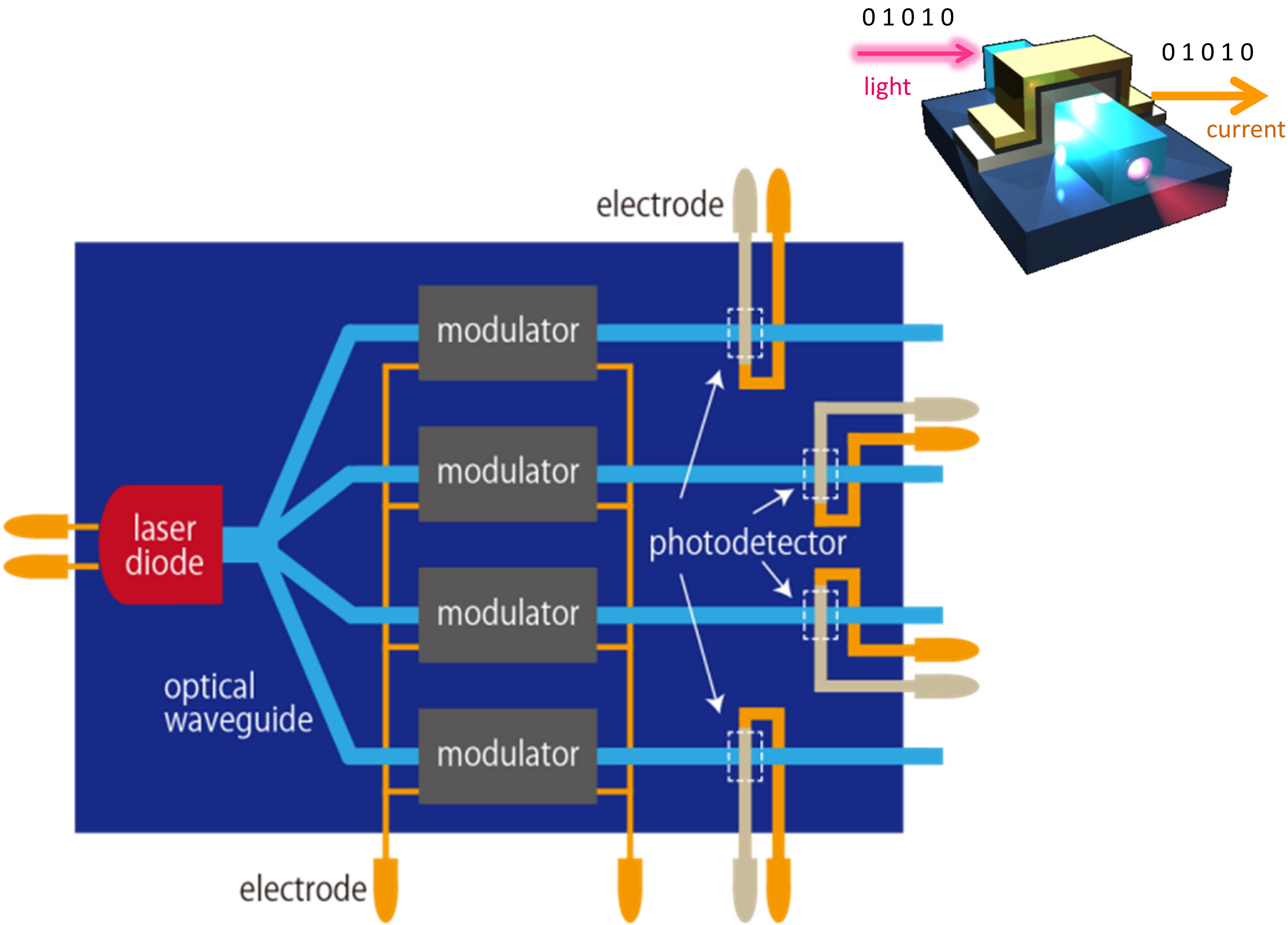
S. Ishii, et al (2014) unpublished

Summary

- MIM photodetectors for optical waveguides
  - Photodetection in visible and NIR including telecom wavelengths
  - Simple & compact geometry
  - Applicable for insulator waveguides (e.g. polymers)
- Transparent photodetecors with TCOs

Acknowledgements

- Strategic Information and Communications R&D Promotion Programme (SCOPE)
- The Japan Prize Foundation



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light
0 1 0 1 0
current
electrode
modulator
modulator
modulator
modulator
laser diode
photodetector
optical waveguide
electrode

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