Characterization of external quantum efficiency of multi-junction solar cells

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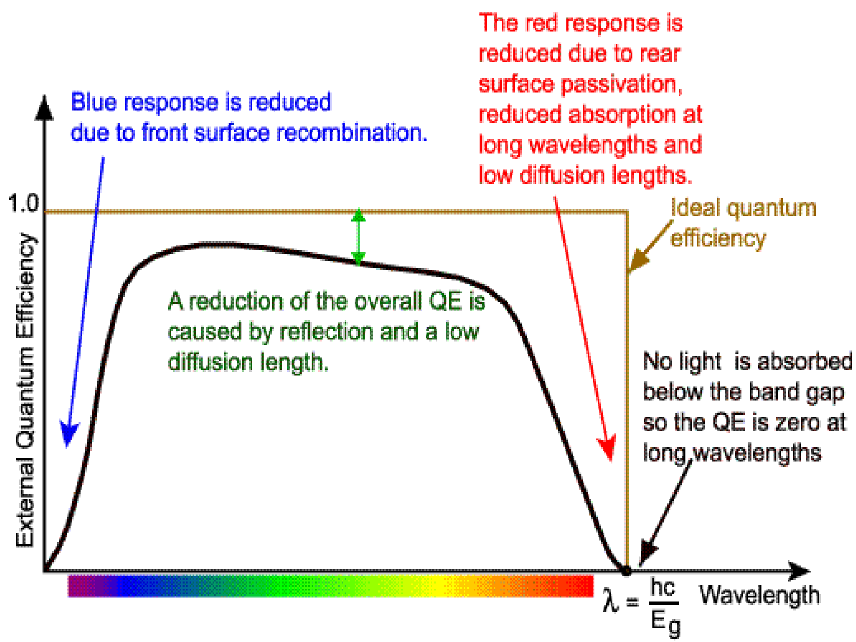
Outline

- Introduction
- Origins of EQE measurement artifacts
- Elimination of EQE measurement artifacts

Quantum efficiency (QE) of solar cells

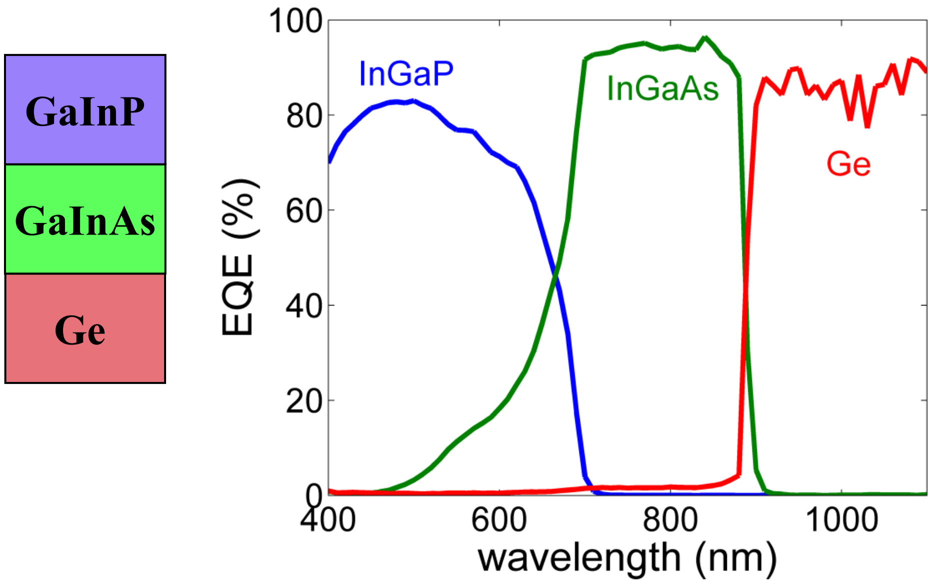
- $\text{QE} = \dfrac{\text{\# of carriers collected by the solar cell}}{\text{\# of photons of a given energy of the incident light}}$
- External quantum efficiency (EQE) vs. internal quantum efficiency (IQE)
- Important for the device design and development
- EQE losses: reflection, parasitic absorption, transmission, and recombination
- Multi-junction (MJ): the degree of current matching



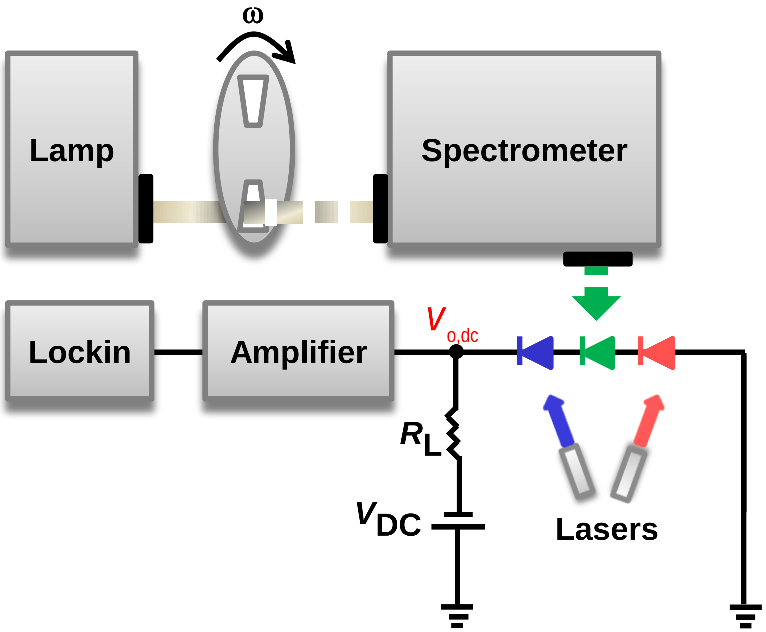
Ref: PVCDROM

Multi-junction (MJ) solar cell EQE measurement

EQE spectrum of triple junction solar cells



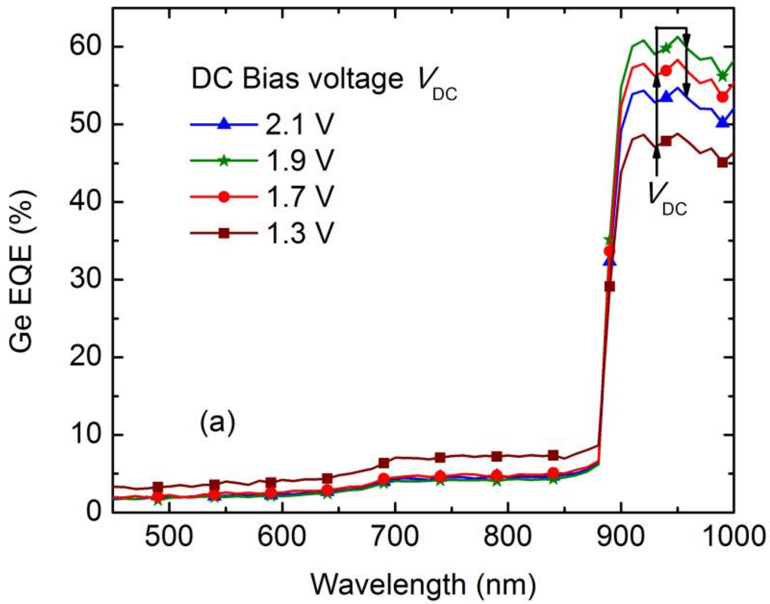
Measurement setup



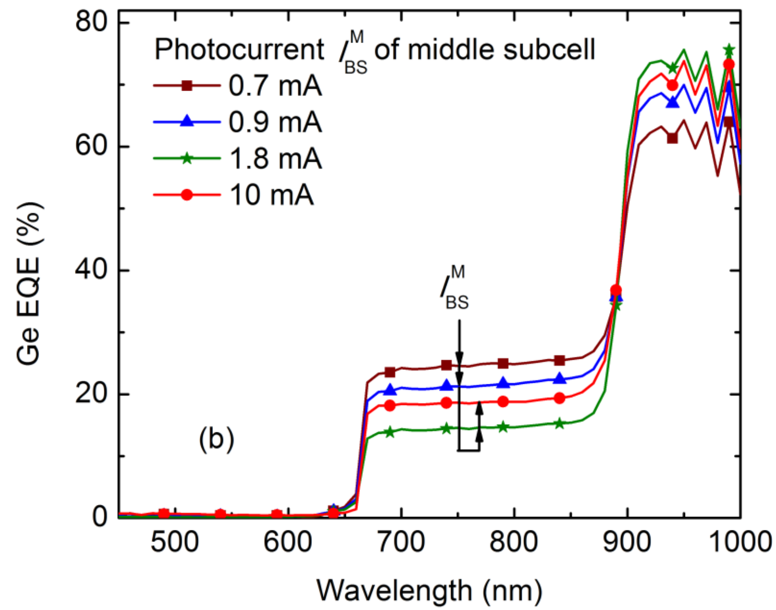
EQE measurement artifacts of MJ solar cells

Measurement artifacts caused by the coupling effects between subcells

Shunt effect



Combined effects of shunt and luminescence coupling



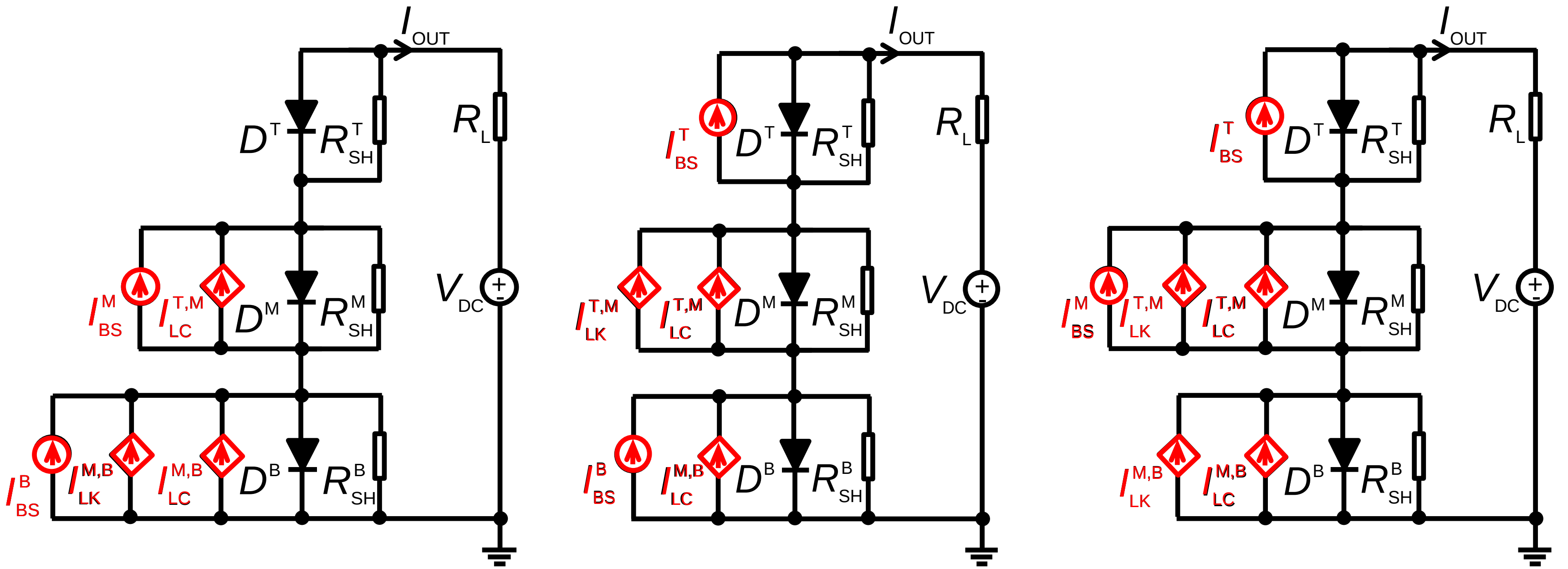
Bias condition

Bias voltage ⟹ shunt effect

Bias light intensity ⟹ luminescence coupling effect

Origins of EQE measurement artifacts

Top subcell Middle subcell Bottom subcell



Optical leakage current: incomplete absorption of bias light in the upper subcell

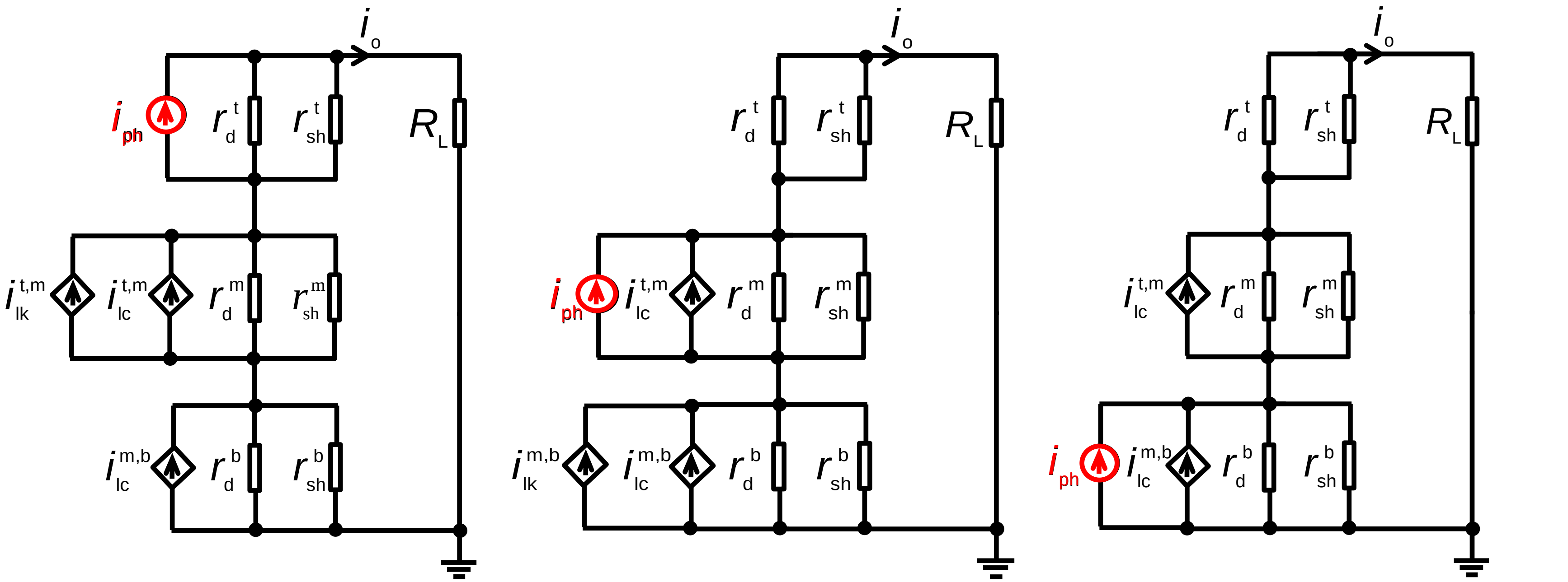
Luminescence coupling current: radiative recombination in the upper subcell

DC bias condition ⟹ subcell operating points

J.-J. Li, et. al., J. Photovolt. 1, 225, 2011.

Origins of EQE measurement artifacts

Top subcell wavelength | Middle subcell wavelength | Bottom subcell wavelength



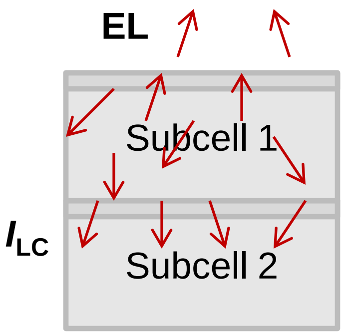
Measurement artifacts arise when $i_o \neq i_{ph}$

Top subcell wavelength	$\frac{i_o}{i_{ph}} = \frac{(r^t // r^t_{sh}) + (\gamma^{t,m} + \alpha^{t,m}_{lk})(r^m // r^m_{sh}) + (\gamma^{t,m} + \alpha^{t,m}_{lk})\gamma^{m,b}(r^b // r^b_{sh})}{(r^t // r^t_{sh}) + (1+\gamma^{t,m})(r^m // r^m_{sh}) + [1+(1+\gamma^{t,m})\gamma^{m,b}](r^b // r^b_{sh}) + R_L}$
Middle subcell wavelength	$\frac{i_o}{i_{ph}} = \frac{(r^m // r^m_{sh}) + (\gamma^{m,b} + \alpha^{m,b}_{lk})(r^b // r^b_{sh})}{(r^t // r^t_{sh}) + (1+\gamma^{t,m})(r^m // r^m_{sh}) + [1+(1+\gamma^{t,m})\gamma^{m,b}](r^b // r^b_{sh}) + R_L}$
Bottom subcell wavelength	$\frac{i_o}{i_{ph}} = \frac{(r^b // r^b_{sh})}{(r^t // r^t_{sh}) + (1+\gamma^{t,m})(r^m // r^m_{sh}) + [1+(1+\gamma^{t,m})\gamma^{m,b}](r^b // r^b_{sh}) + R_L}$

J.-J. Li, et. al., J. Photovolt. 1, 225, 2011.

Characterization of luminescence coupling strength

Relation between electroluminescence (EL) and luminescence coupling



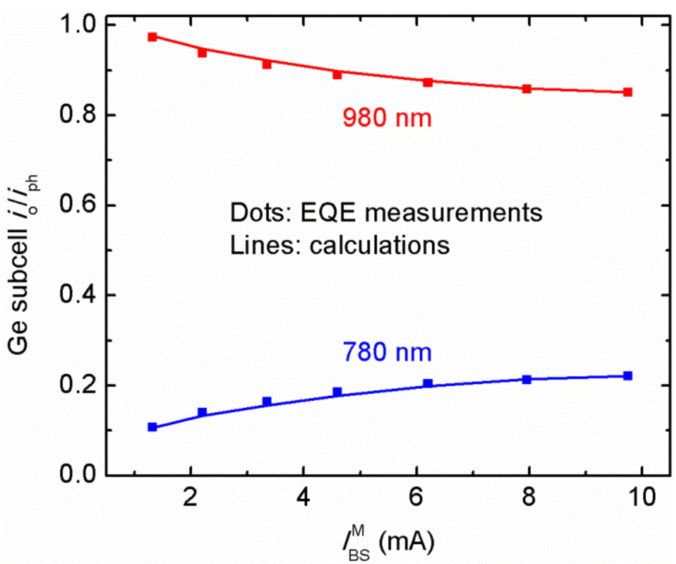
$$\int \frac{L(\lambda)\lambda}{hc} d\lambda = \frac{\chi}{q} I_{LC}$$

χ is a scaling factor

So the luminescence coupling efficiency is

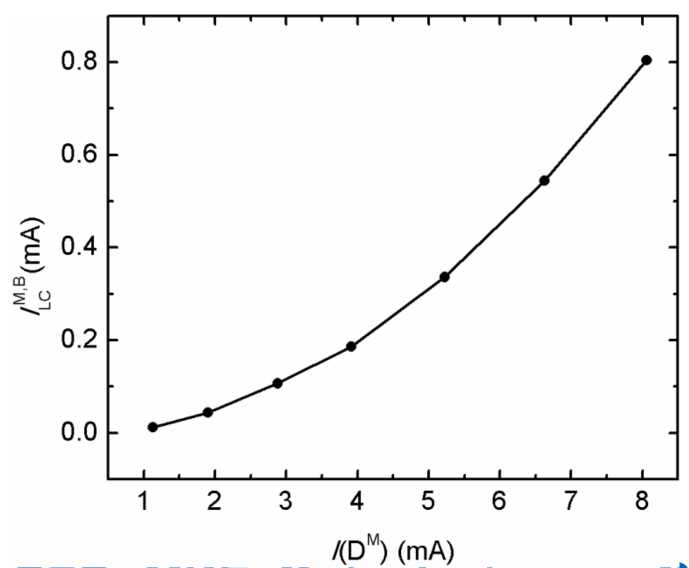
$$\alpha_{lc} = \frac{dI_{LC}}{dI(\mathrm{D})} = \frac{d\left(q\int \frac{L(\lambda)\lambda}{hc} d\lambda \Big/ \chi\right)}{dI(\mathrm{D})}$$

Luminescence coupling effect on EQE



$\Rightarrow$ χ, α_{lc}, α_{lk}

Luminescence coupling current



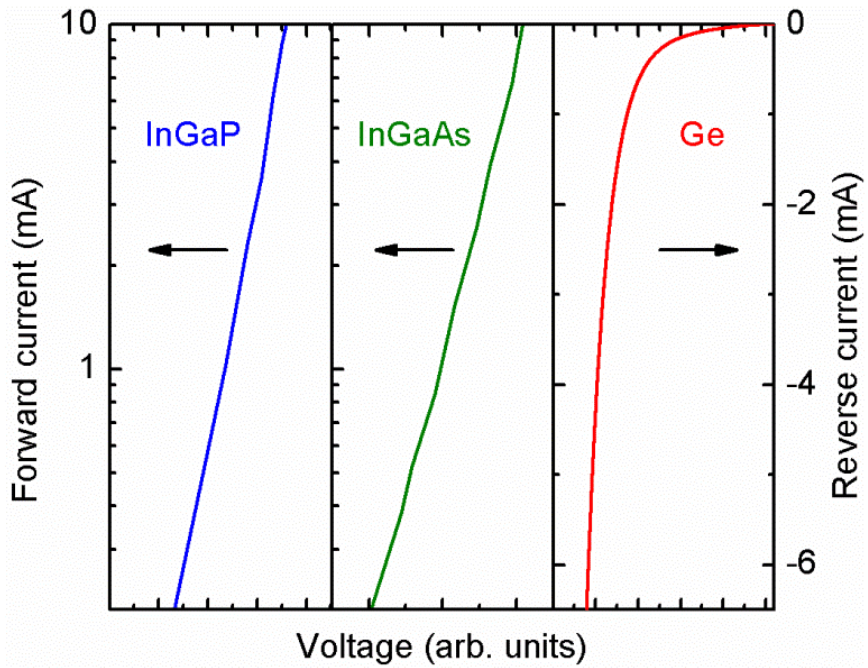
J.-J. Li, et. al., J. Photovolt. 1, 225, 2011. S. H. Lim, J.-J. Li, et. al., Prog. Photovolt. Res. Appl., doi: 10.1002/pip.1215, 2011.

Characterization of small signal resistances

Subcell *I*-*V* extraction

- I_{sc}-V_{oc} method for the forward biased top two subcells
- Reverse voltage sweep for the reverse biased Ge subcell

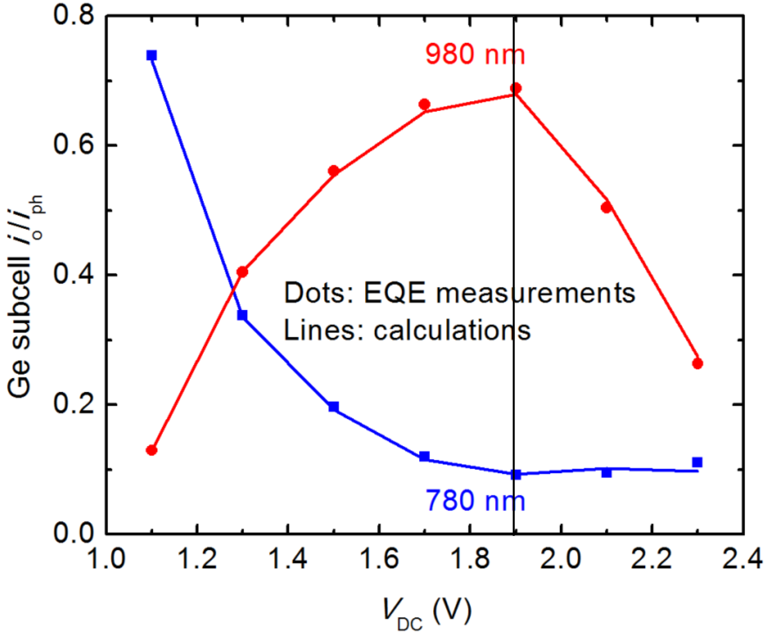
Small signal resistance = slope of *I*-*V* at the operating point



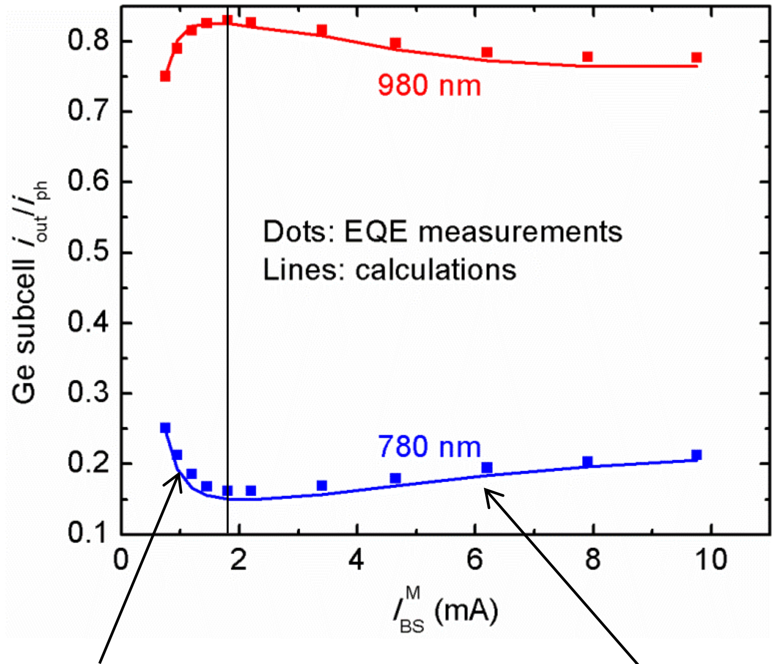
J.-J. Li, et. al., J. Photovolt. 1, 225, 2011.

Origins of EQE measurement artifacts

Optimal bias voltage



Optimal bias light intensity



Shunt

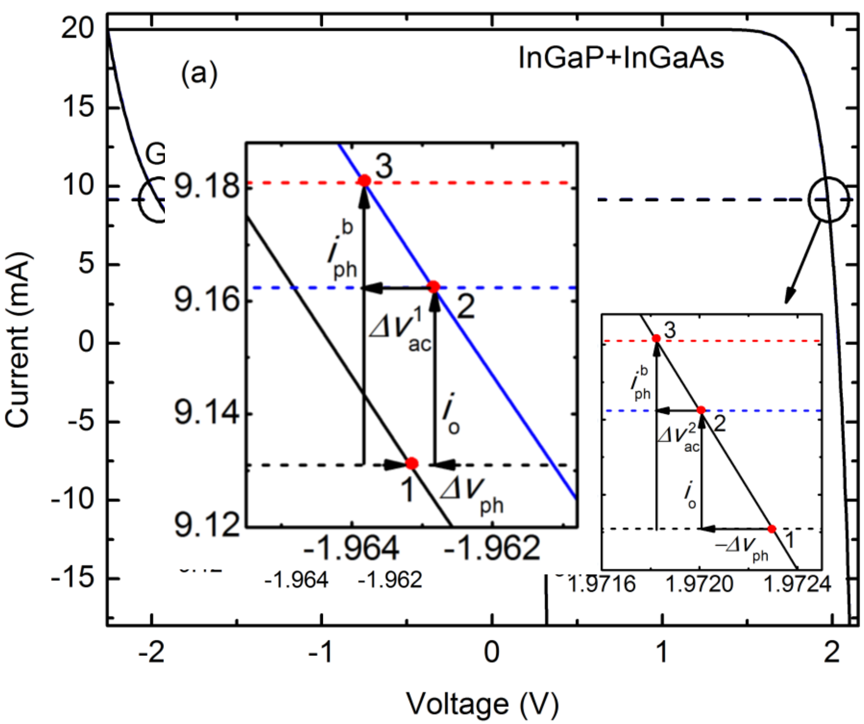
Shunt

Luminescence coupling

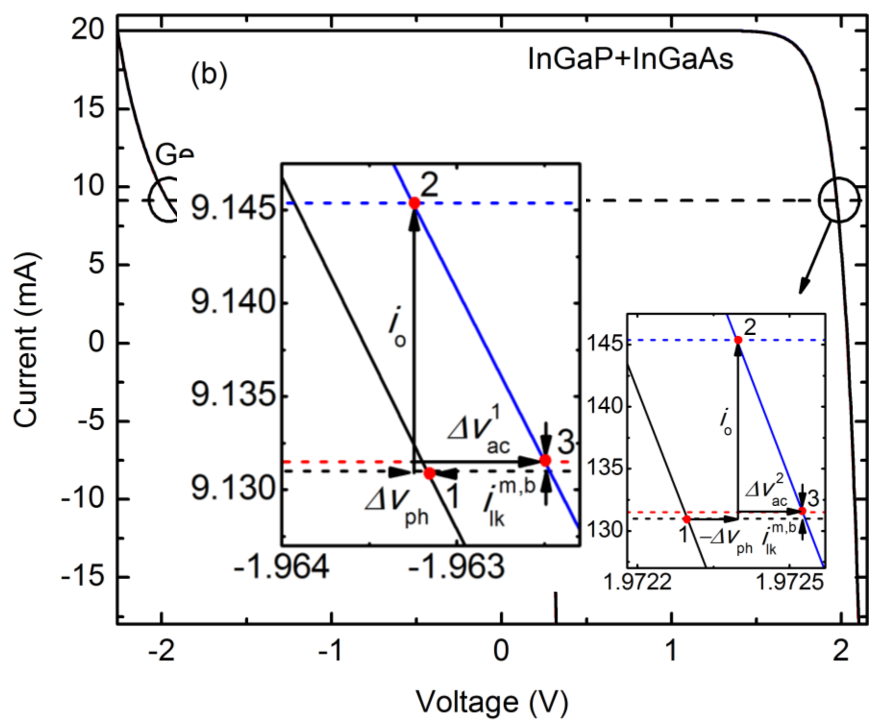
J.-J. Li, et. al., J. Photovolt. 1, 225, 2011.

Elimination of EQE measurement artifacts using a pulse voltage bias

Ge wavelength range



InGaAs wavelength range



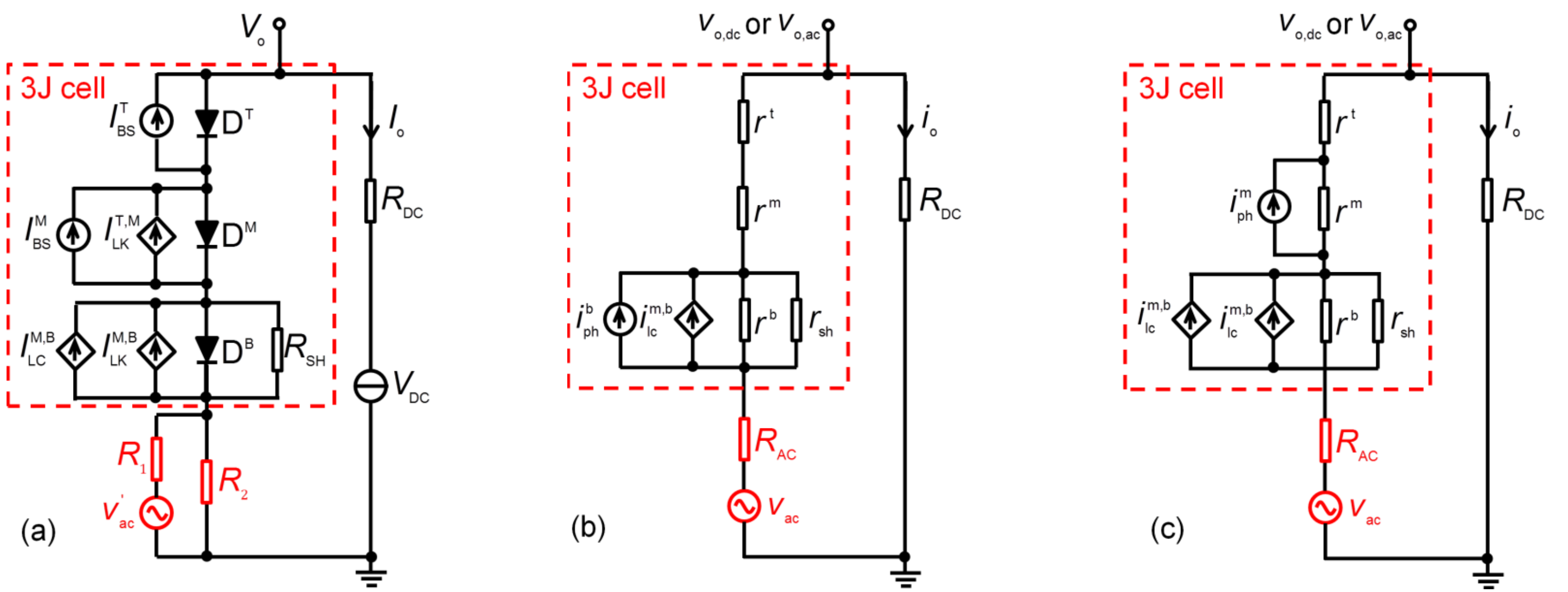
MBE Optoelectronics Group

J.-J. Li, et. al., Prog. Photovolt. Res. Appl., in review.

J.-J. Li, et. al., Proc. SPIE 8256, 825616, 2012.

Elimination of EQE measurement artifacts using a pulse voltage bias

Bias condition | Ge wavelength range | InGaAs wavelength range

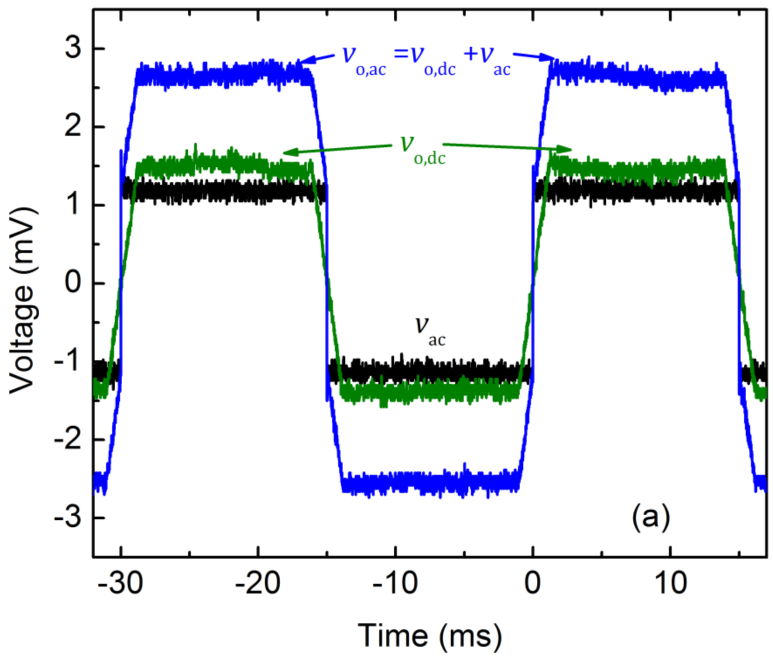


(b)	$i_o = \dfrac{i_{ph}^b\, r^b r_{sh}/\left(r^b + r_{sh}\right) + v_{ac}}{r^t + r^m + \left(1+\alpha_{lc}^{m,b}\right) r^b r_{sh}/\left(r^b + r_{sh}\right) + R_{AC} + R_{DC}}$	$v_{ac}^0 = \dfrac{v_{o,ac}^0}{R_{DC}}\left[r^t + r^m + \alpha_{lc}^{m,b}\, r^b r_{sh}^b/\left(r^b + r_{sh}^b\right) + R_{AC} + R_{DC}\right]$
(c)	$i_o = \dfrac{i_{ph}^m\left[r^m + \left(\alpha_{lc}^{m,b} + \alpha_{lk}^{m,b}\right) r^b r_{sh}^b/\left(r^b + r_{sh}^b\right)\right] + v_{ac}}{r^t + r^m + \left(1+\alpha_{lc}^{m,b}\right) r^b r_{sh}^b/\left(r^b + r_{sh}^b\right) + R_{AC} + R_{DC}}$	$v_{ac}^0 = i_{ph}^m \left[\begin{array}{l}\alpha_{lk}^{m,b} r^t + \left(\alpha_{lk}^{m,b} - 1\right) r^m + \left(\alpha_{lk}^{m,b} - 1\right)\alpha_{lc}^{m,b}\, r^b r_{sh}/\left(r^b + r_{sh}\right) \\ +\alpha_{lk}^{m,b}\left(R_{AC} + R_{DC}\right)\end{array}\right]$

J.-J. Li, et. al., Prog. Photovolt. Res. Appl., in review.
J.-J. Li, et. al., Proc. SPIE 8256, 825616, 2012.

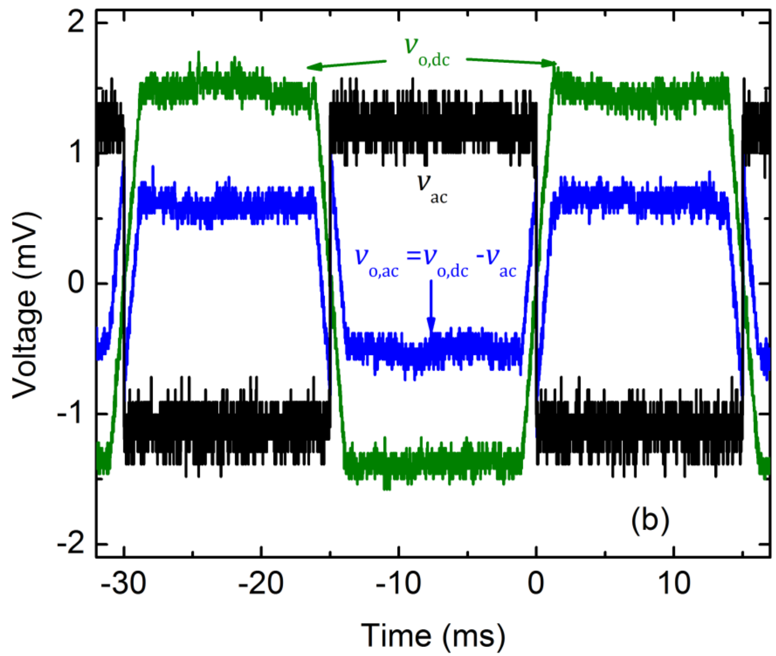
Waveforms of EQE and pulse bias voltage

Ge wavelength range



The pulse voltage is in phase with the chopper

InGaAs wavelength range

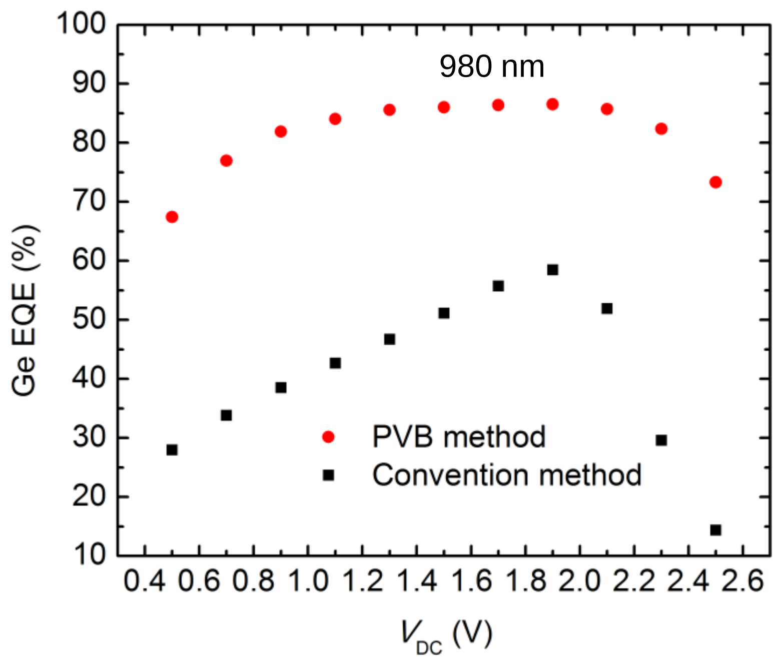


The pulse voltage is in anti-phase with the chopper

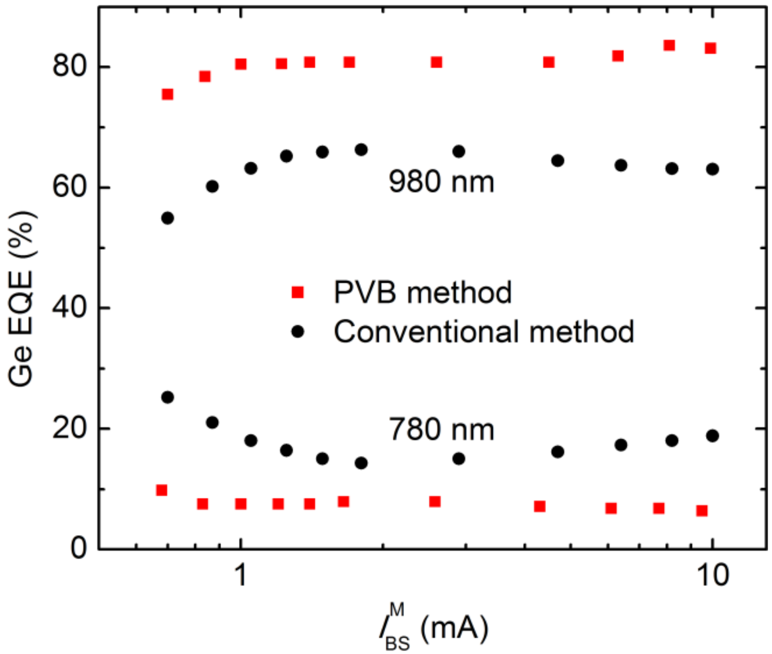
J.-J. Li, et. al., Prog. Photovolt. Res. Appl., in review.

Measurement results

Shunt effect



Combined effects of shunt and luminescence coupling



The pulse voltage bias method is susceptible to the variations of subcell characteristics

The DC bias condition should be chosen properly

J.-J. Li, et. al., Prog. Photovolt. Res. Appl., in review.
J.-J. Li, et. al., Proc. SPIE 8256, 825616, 2012.

Conclusions

- EQE measurement artifacts of multi-junction solar cells are caused by the shunt effect and luminescence coupling effect.
- Models are built to analyze the EQE measurement artifacts and methods are developed to characterize them.
- It is demonstrated that the EQE measurement artifacts of the Ge subcells of triple junction solar cells can be minimized using proper voltage and light biases.
- A pulse voltage bias method is developed to eliminate the EQE measurement artifacts. It effectively eliminates the measurement artifacts of the Ge subcells of triple junction solar cells

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