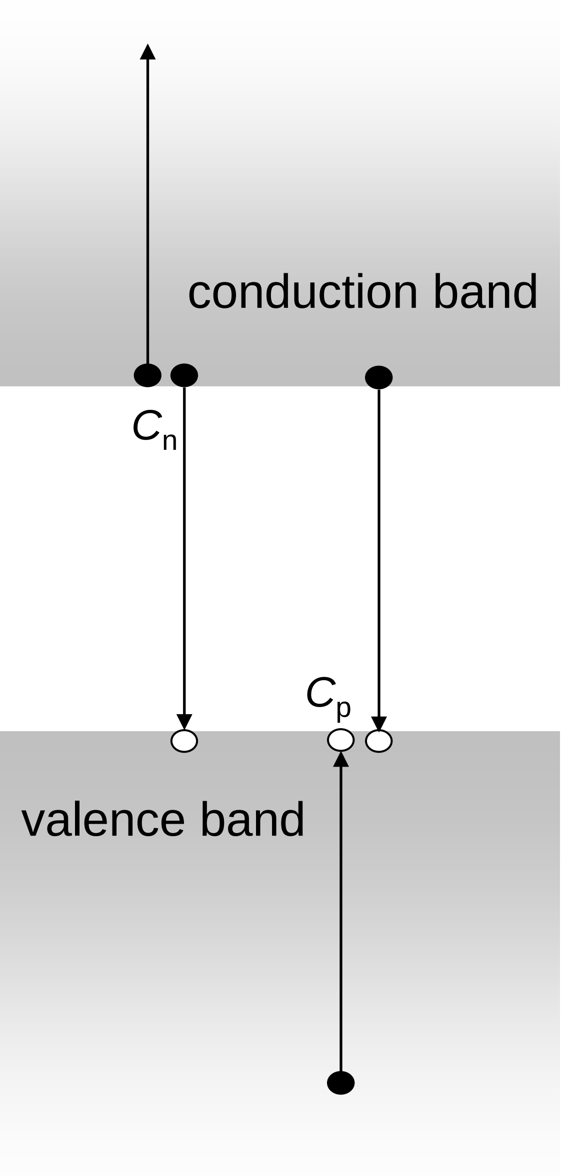
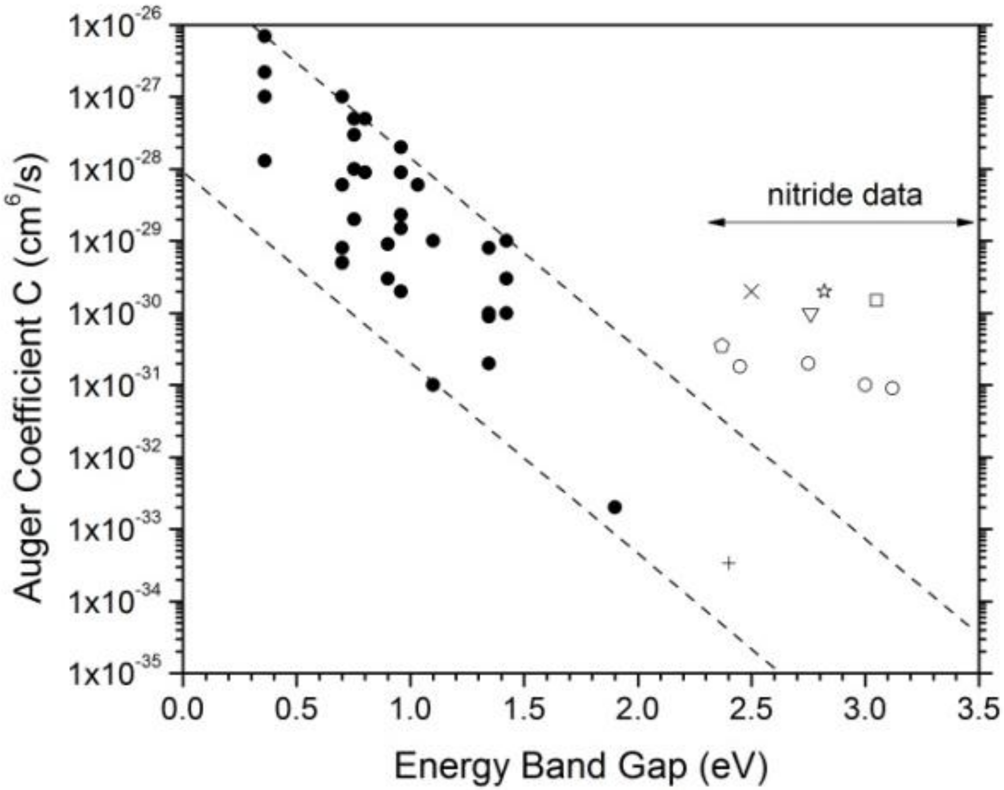
# Auger Recombination

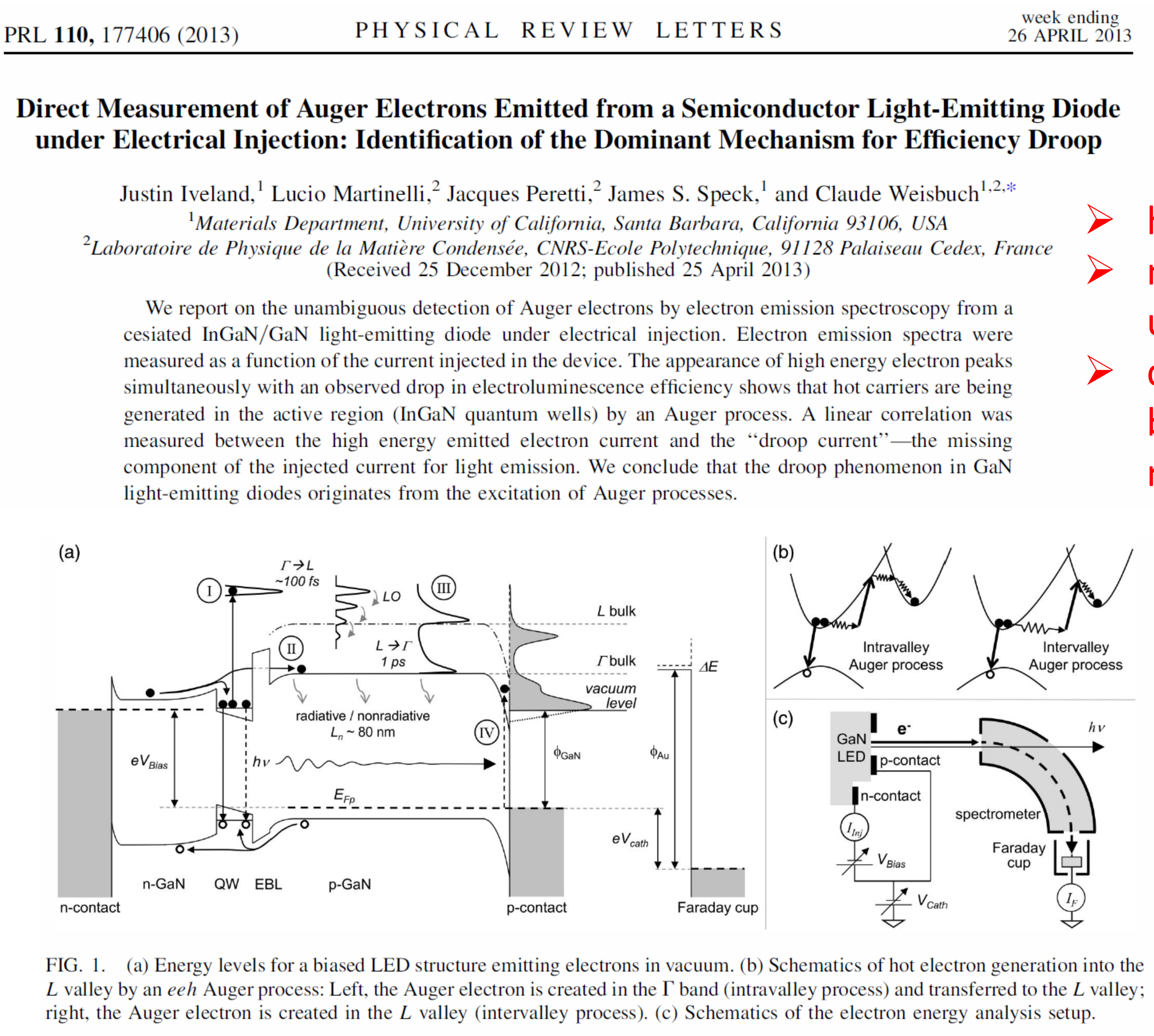


$$R_{Auger} = ( C_n\, n + C_p\, p ) ( np - n_i^2 )$$



How to determine C for InGaN QWs ?

# Direct Experimental Evidence



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## Direct Measurement of Auger Electrons Emitted from a Semiconductor Light-Emitting Diode under Electrical Injection: Identification of the Dominant Mechanism for Efficiency Droop

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We report on the unambiguous detection of Auger electrons by electron emission spectroscopy from a cesiated InGaN/GaN light-emitting diode under electrical injection. Electron emission spectra were measured as a function of the current injected in the device. The appearance of high energy electron peaks simultaneously with an observed drop in electroluminescence efficiency shows that hot carriers are being generated in the active region (InGaN quantum wells) by an Auger process. A linear correlation was measured between the high energy emitted electron current and the "droop current"—the missing component of the injected current for light emission. We conclude that the droop phenomenon in GaN light-emitting diodes originates from the excitation of Auger processes.

FIG. 1. (a) Energy levels for a biased LED structure emitting electrons in vacuum. (b) Schematics of hot electron generation into the *L* valley by an *eeh* Auger process: Left, the Auger electron is created in the Γ band (intravalley process) and transferred to the *L* valley; right, the Auger electron is created in the *L* valley (intervalley process). (c) Schematics of the electron energy analysis setup.

- hot Auger electrons detected
- magnitude of effect on droop unclear (C= ?)
- disputed by other authors based on fast p-side carrier relaxation

# Experimental Results for C of InGaN QWs

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## On the uncertainty of the Auger recombination coefficient extracted from InGaN/GaN light-emitting diode efficiency droop measurements

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TABLE I. Recombination parameter sets extracted from the measurements in Fig. 2 using different models.

| Model | $A/10^6\,s^{-1}$ | $B/10^{-12}\,cm^3/s$ | $C/10^{-31}\,cm^6/s$ |
|---|---|---|---|
| ABC model | 2.6 | 3.0 | 1.0 |
| ABC model with n = 2p | 3.9 | 1.5 | 0.16 |
| APSYS | $14^a$ | $(17^a)$ | $2.5^a$ |
| Quatra/Cels | 3.1 | $4.1^b$ | $1.7^b$ |
| Quatra/Cels (hot carriers) | 3.1 | $4.1^b$ | $0.8^b$ |
| Quatra/Cels (no polarization) | 5.9 | 17.7 | 7.0 |

[a]Electron-hole separation is considered separately.
[b]Values B(i) and C(i) given at $i_{peak} = 5$ A/cm$^2$.

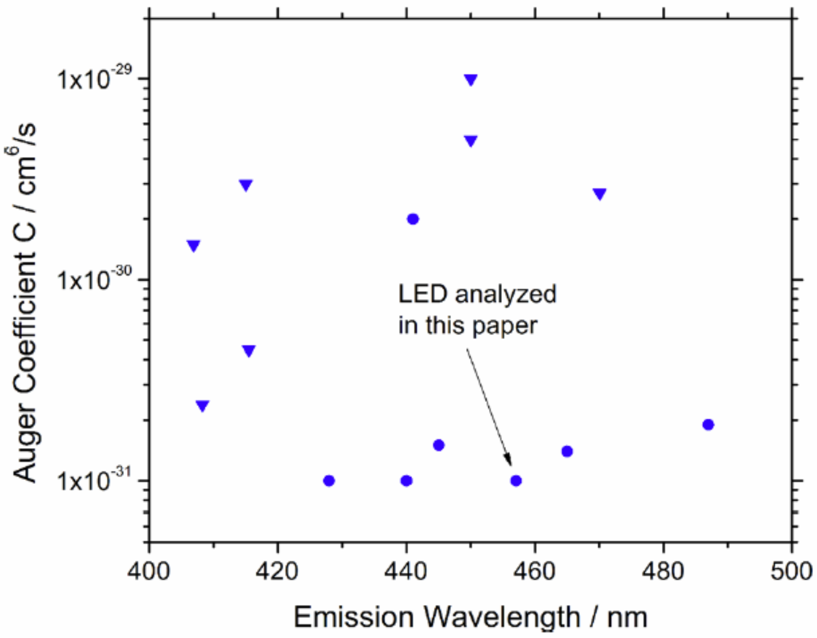


FIG. 1. Published Auger coefficients C extracted from measurements on devices with InGaN active layers of different emission wavelength (circles—single active layer, triangles—multiple quantum wells).

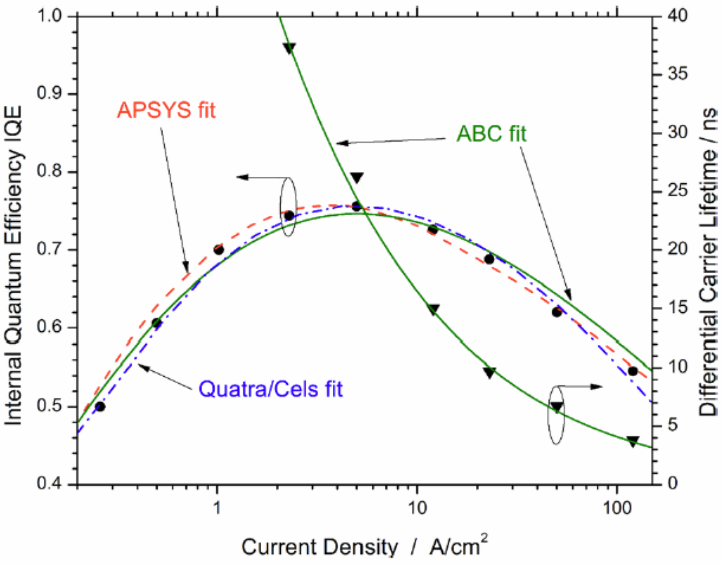
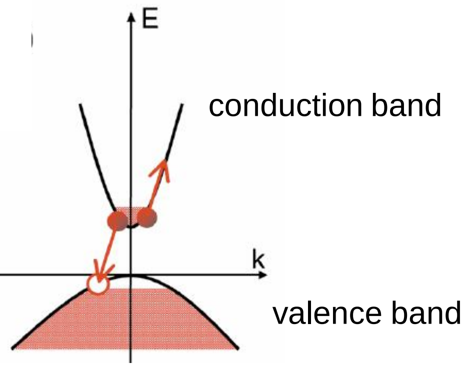


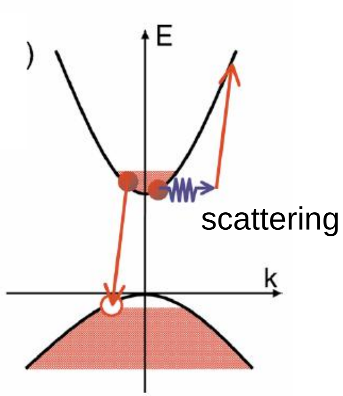
FIG. 2. Internal quantum efficiency IQE and differential carrier lifetime as function of current density (symbols—measurements, lines—modeling).

# Theoretical Results for C in InGaN

direct Auger
recombination



indirect Auger
recombination

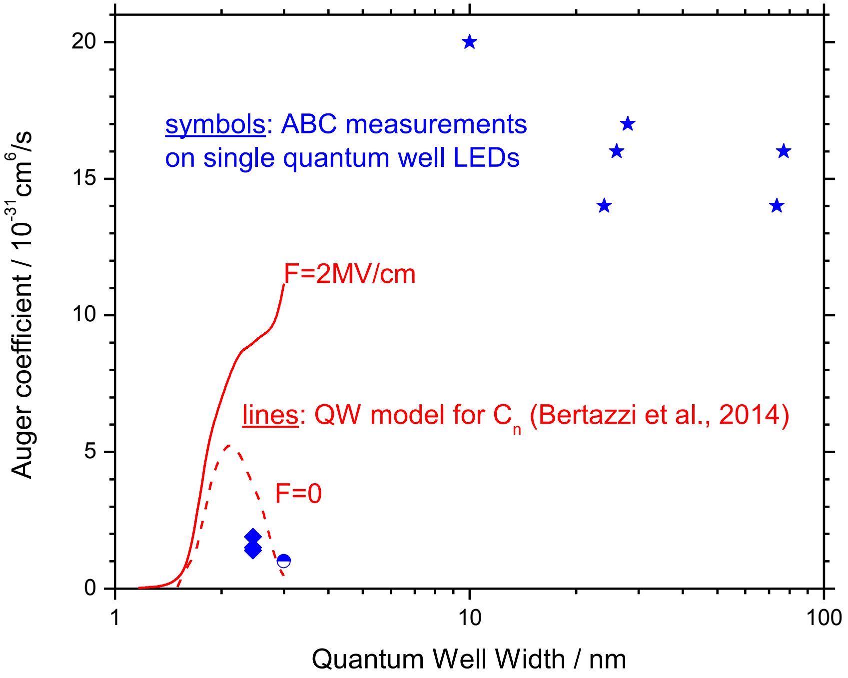


atomistic model calculations of the Auger parameter

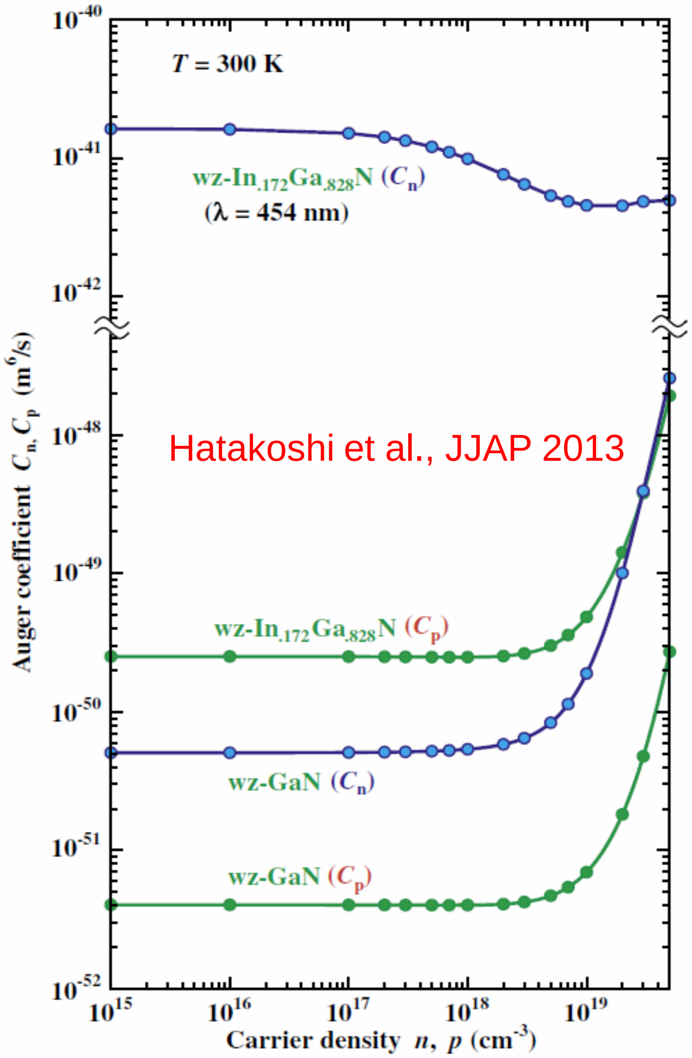
C = 3E-34 cm$^6$/s (QW, direct) [Hader et al., APL 2008] KP band structure
C < 2E-30 cm$^6$/s (bulk, direct) [Delaney et al., APL 2009] inter conduction-band transitions
C < 5E-33 cm$^6$/s (bulk, direct) [Bertazzi et al., APL 2010] inter conduction-band transitions
C < 2E-31 cm$^6$/s (bulk, indirect) [Kioupakis et al., APL 2011] indirect
C < 1E-31 cm$^6$/s (bulk, indirect) [Bertazzi et al., APL 2012] indirect
C < 9E-31 cm$^6$/s (QW, direct) [Vaxenburg et al., APL 2013] KP, zinc-blende
C < 5E-31 cm$^6$/s (QW, direct) [Bertazzi et al., APL 2013] strong d-dependence
C < 7E-31 cm$^6$/s (QW, direct, 2MV/cm) [Bertazzi et al., NUSOD 2014]

# Theoretical Sensitivities of the Auger Coefficient

quantum well thickness & electric field



carrier density (bulk)



Hatakoshi et al., JJAP 2013

- strong dependence on QW width and field
- C varies with carrier density ($Cn^3$ not correct)

# What do we need to do ?

Develop theory for Auger recombination in InGaN and AlGaN quantum wells which includes the influence of

- *indirect transitions*
- *polarization field*
- *composition*
- *thickness & shape*
- *non-uniformities*