> 73% CW Wall-Plug Efficiency at High Powers from 0.94-µm and 0.98-µm Emitting Laser Diodes

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Sandrio Elim, Damian Wise, Jun Wang, Suhit Das, Jason Farmer and Mark DeVito

** Our work to improve 9xx-nm device efficiency is supported by DARPA under the SHEDs program contract number: MDA972-03-C-101. This material is approved for public release, distribution unlimited*

nLight Overview

- **History**
  - **Founded in 2000**
  - **Over 100 employees**
- **Technology**
  - **High power laser diodes from 630 to 1900 nm**
  - **Broad range of packages**
- **Production**
  - **60,000 sq ft vertically integrated manufacturing facility**
  - **Complete capabilities with MOCVD through packaging**

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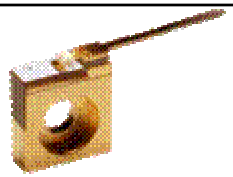
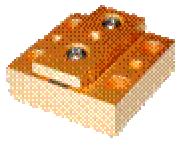
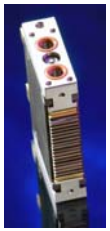
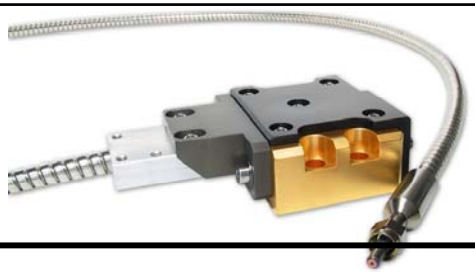
nLight's products range from several Watts to several tens of kW

Product category	nLight product examples
Single Emitter <5W	 
Diode Arrays 40 to 100 Watts	 
Stacks of Arrays >100W	 
Fiber Bundled Arrays < 40 Watts	

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nLight laser diode technology milestones

Capability	Key demonstrations
6xx nm	• 60 Watts CW
8xx nm	• 364 Watts CW
9xx nm	• Over 75% efficiency
14xx nm	• 88 Watts CW
Packaging	• High reliability at 100 Watt CW product

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Contents

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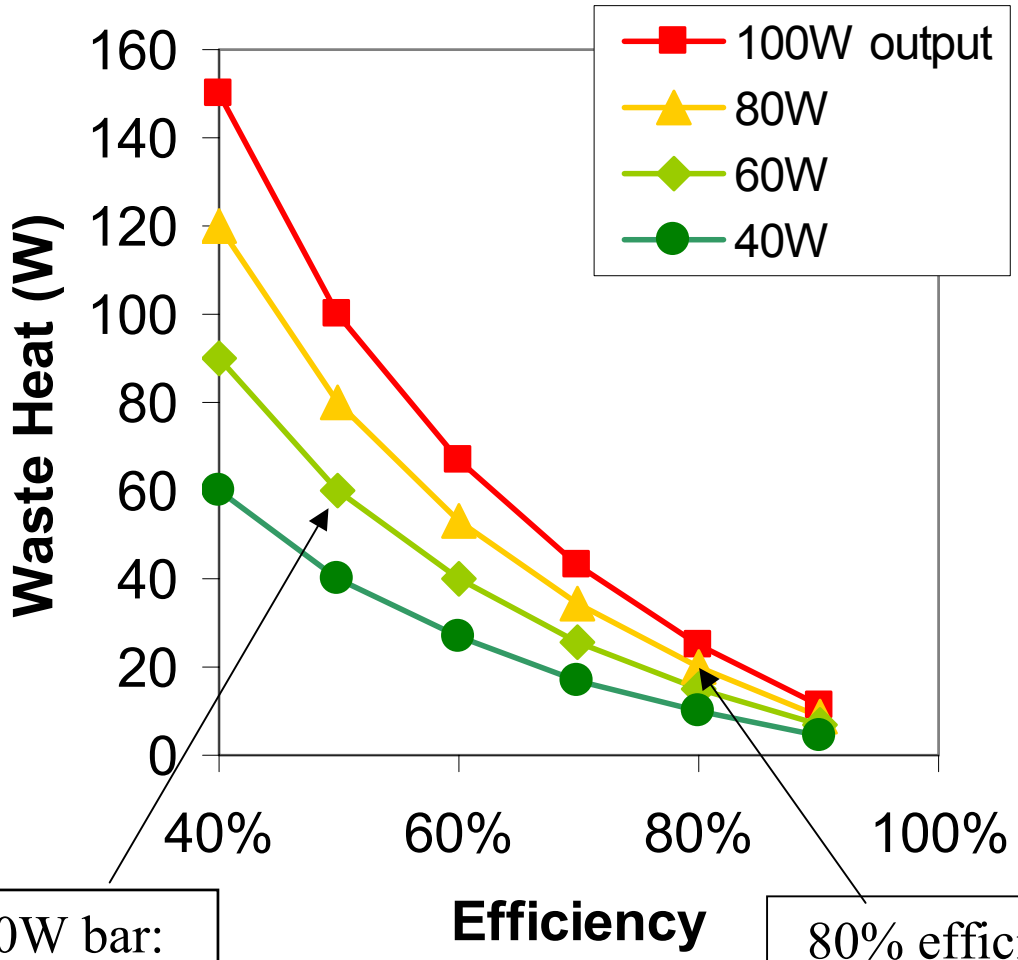
Simpler Thermal Management with Increased Efficiency

> 3x Reduction in Heat Dumped into Cooling System



50% efficient 60W bar:
60W heat dumped per bar

80% efficient 80W bar:
20W heat dumped per bar

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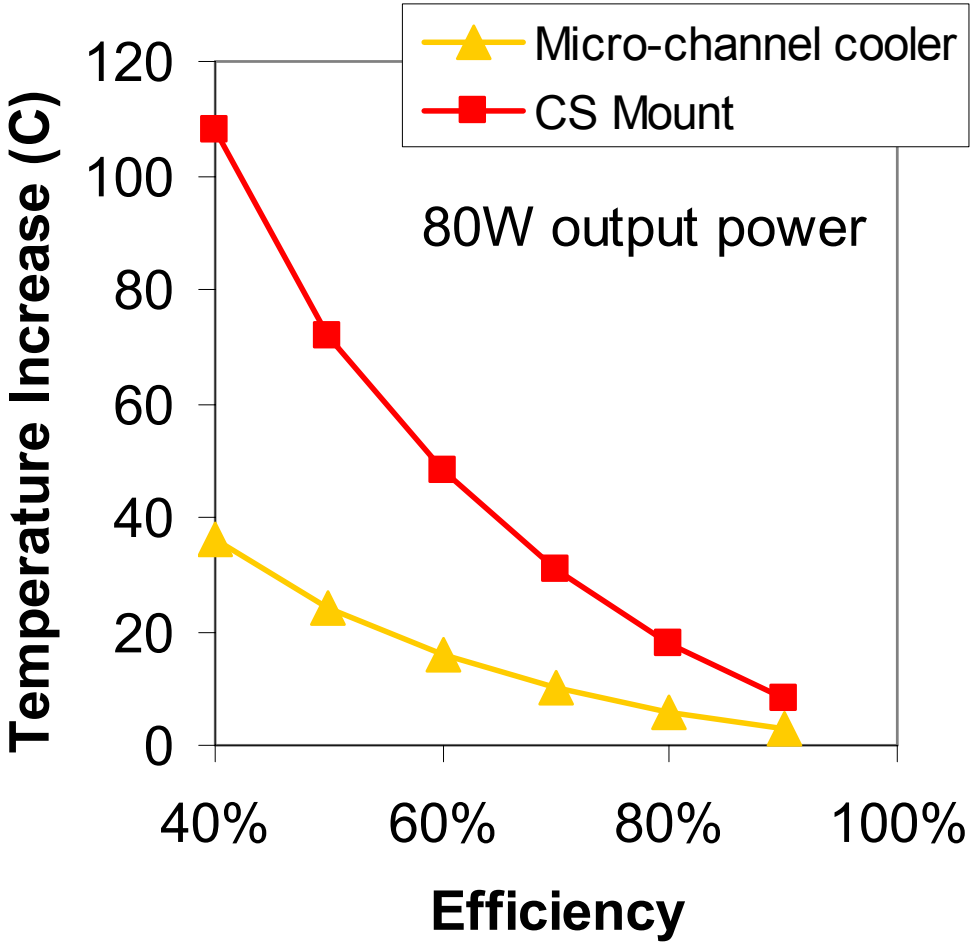
Bars Operate Cooler with Increased Efficiency



Improve efficiency of bar from 50%-80%
Reduce CW temperature of an 80W bar by > 20C

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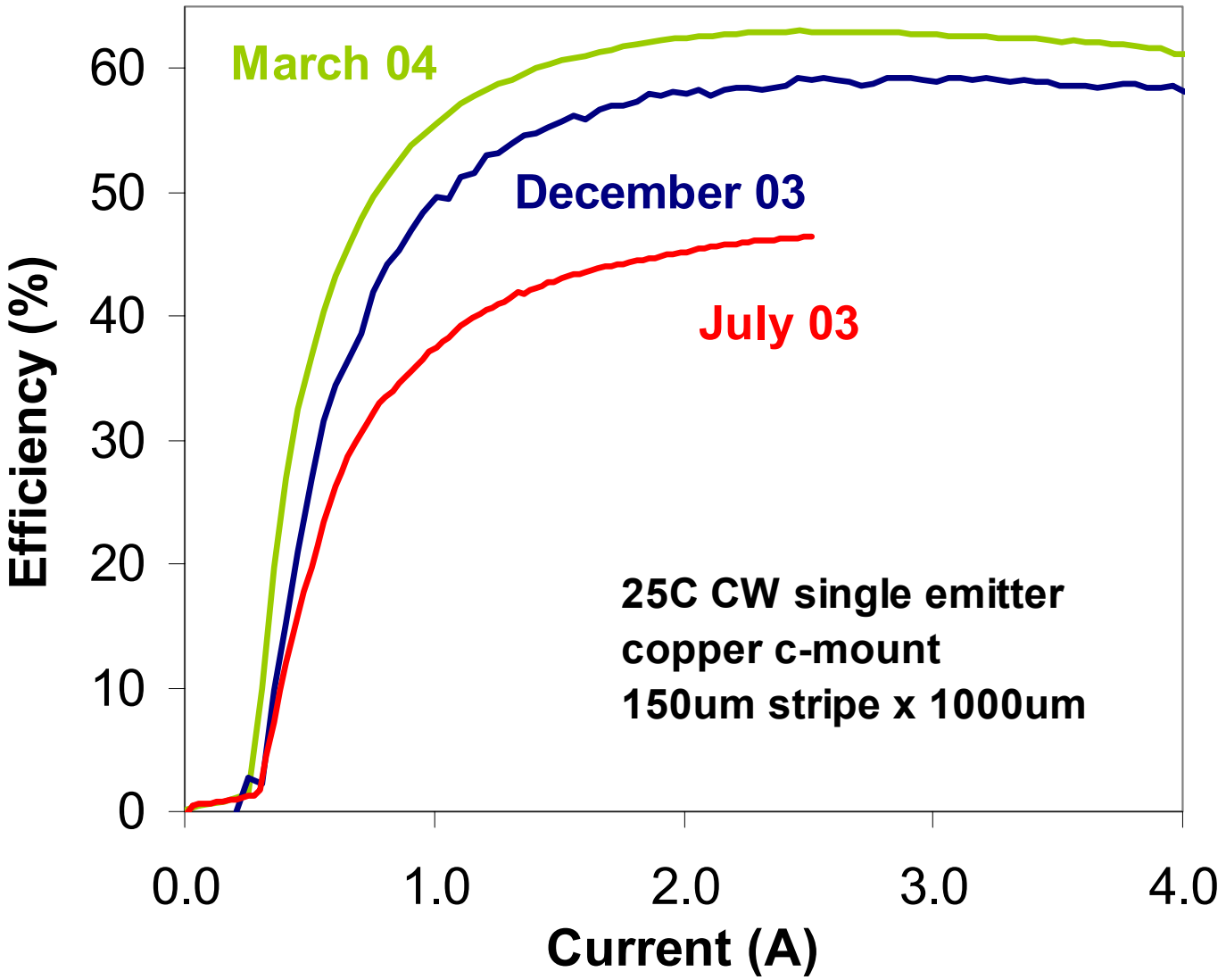
Rapid Early Progress



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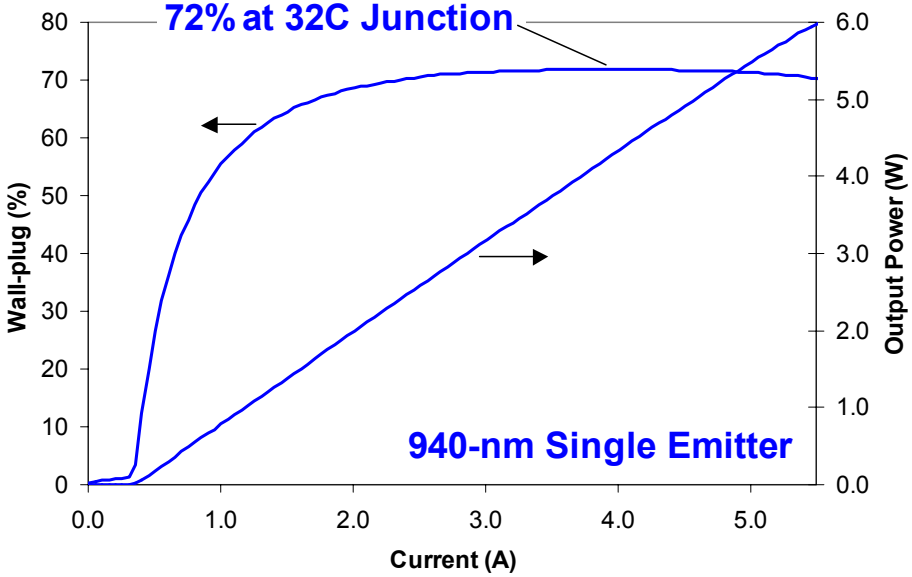
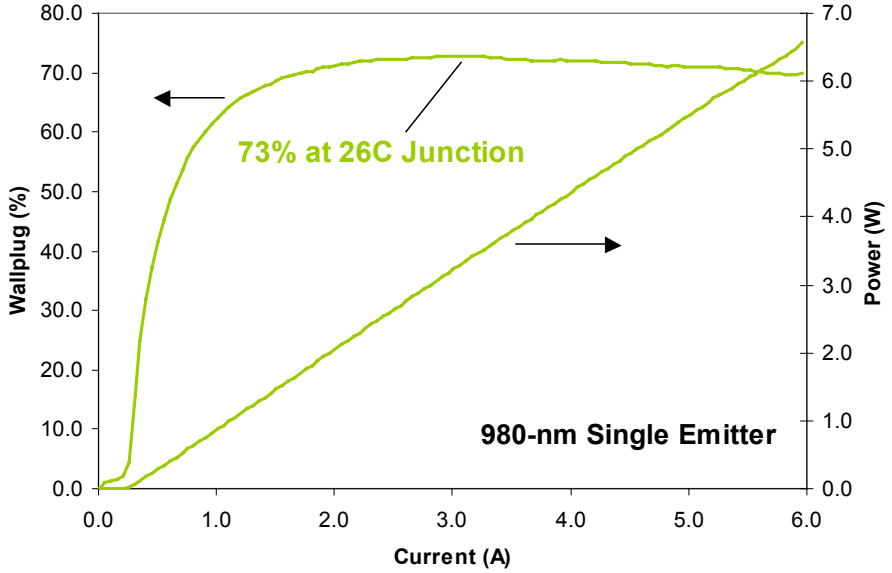
Stable, Wavelength Independent 73% Achieved





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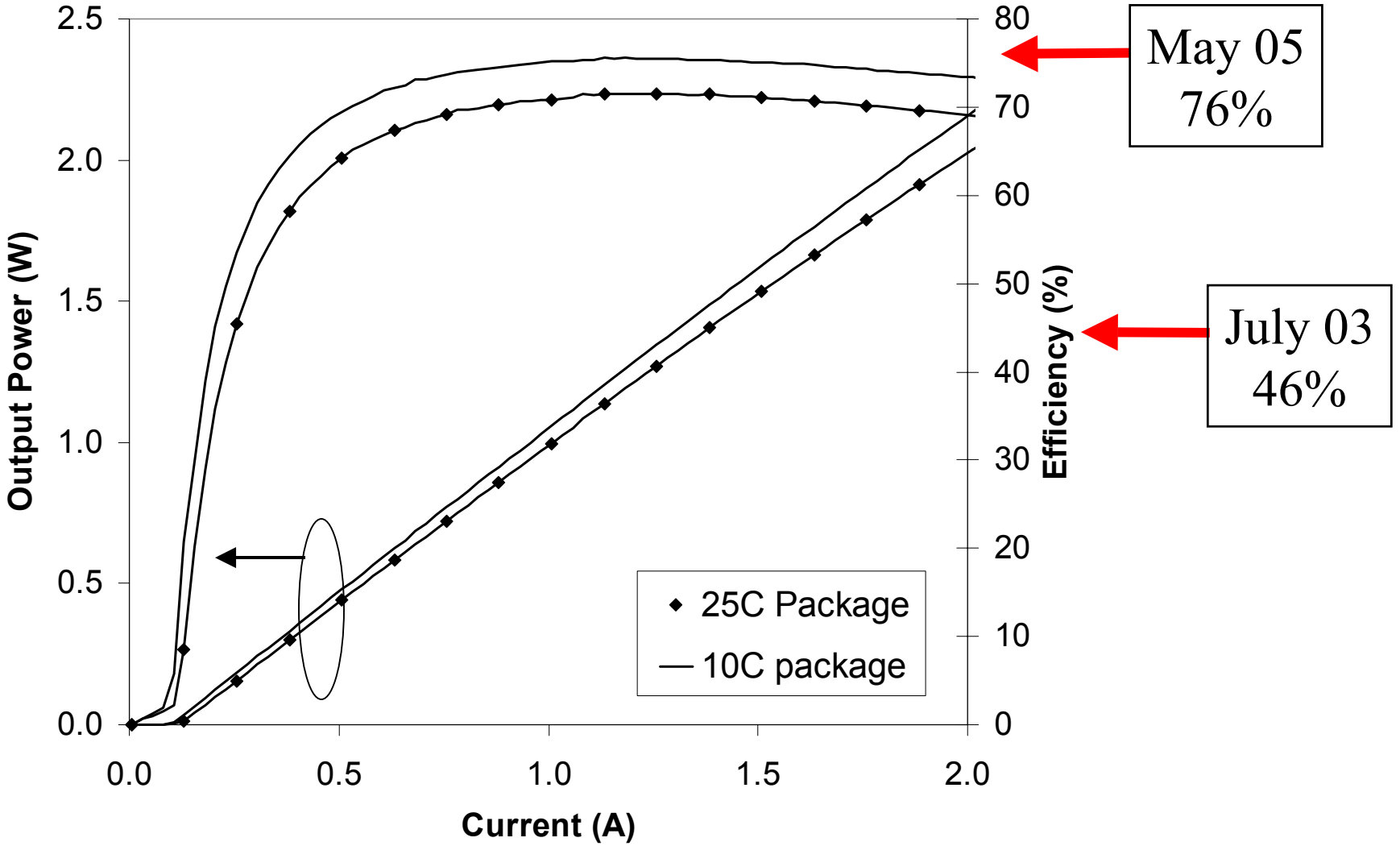
Latest Peak Performance Design: 76% Wall-plug



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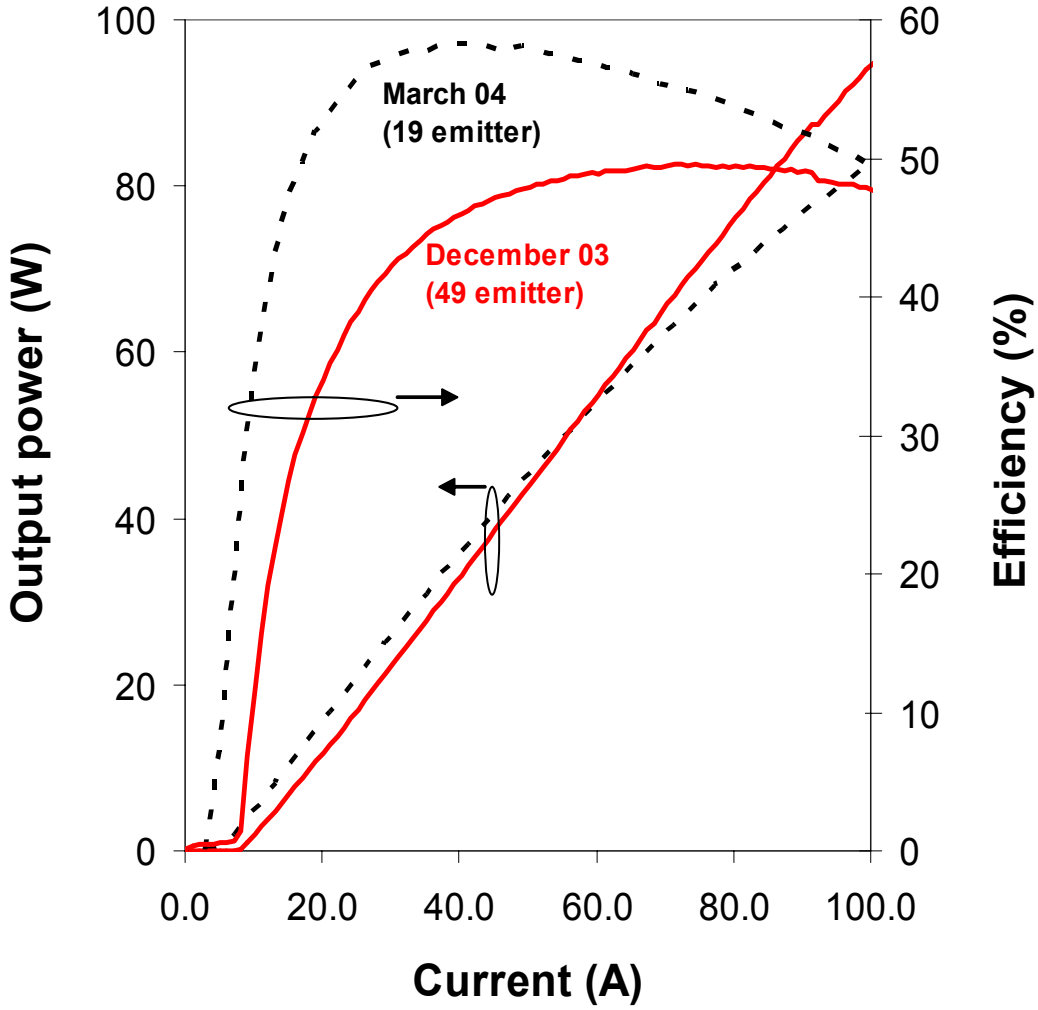
Bars: Initial Rapid Improvement



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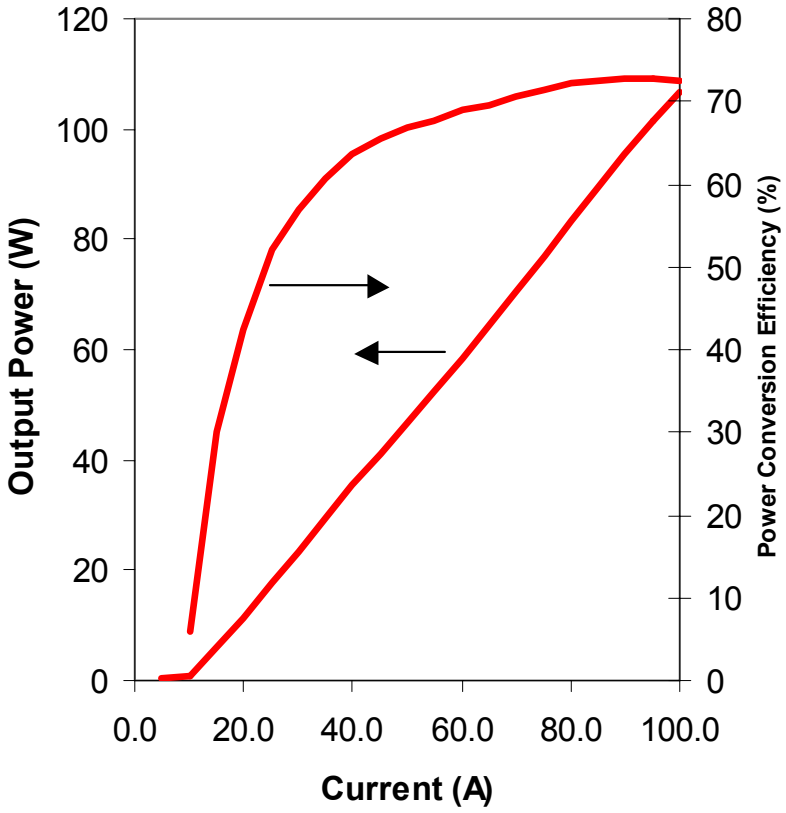
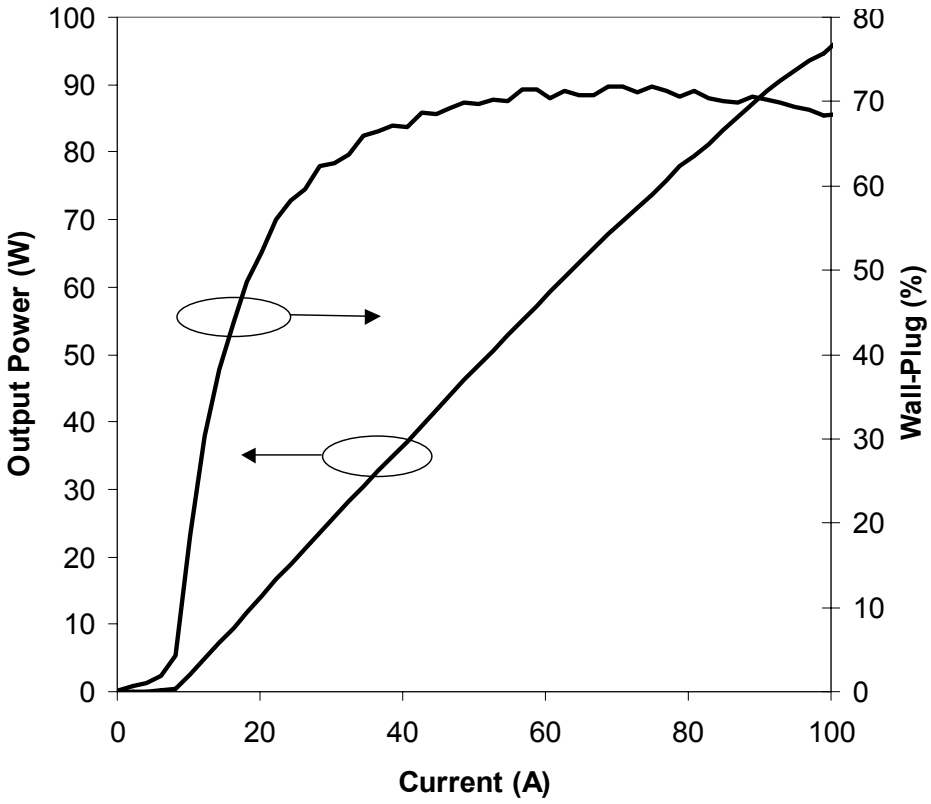
High Efficiency Bars: 73% 100W QCW, 72% 70W CW



50% fill factor 1mm cavity 25C
QCW test (200μs, 100Hz)



50% fill factor 1mm cavity
35C Junction CW test

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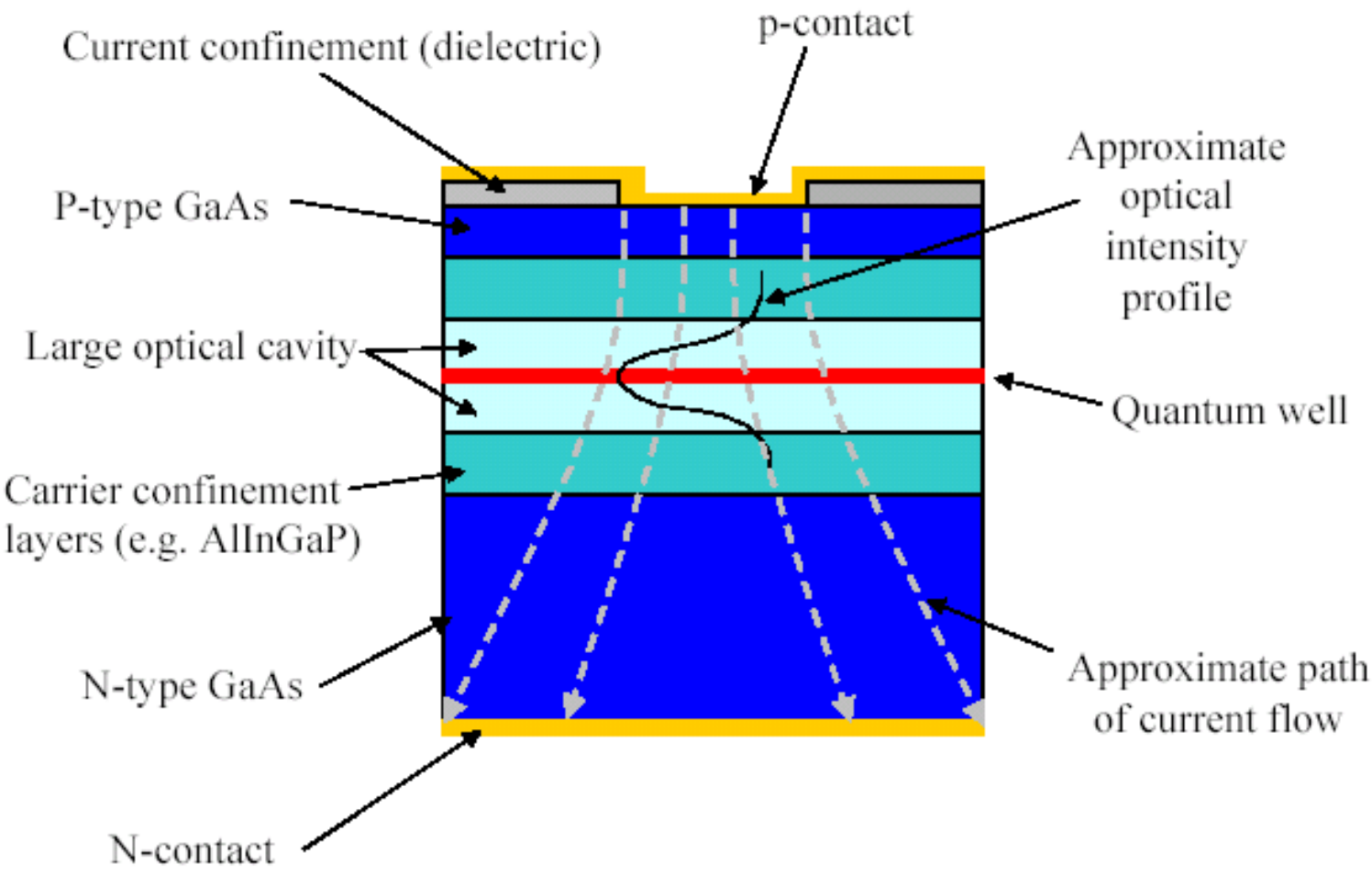
Laser Cross-Section



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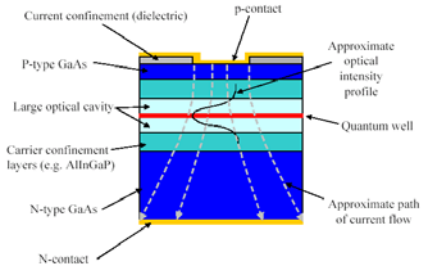
Overall Design Approach



- **Break down all contributors to laser efficiency**
  - Characterize, model, optimize
- **Optimize materials and interfaces by experiment**
  - Contact / interface resistance
  - Bulk mobility
  - Low temperature photoluminescence
- **Systematic approach**
  - Rigorous physics-based modeling
  - Detailed root cause materials analysis
- **Use high performance facet passivation**
  - Open up design space

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3 key Terms Limit Power Conversion Efficiency

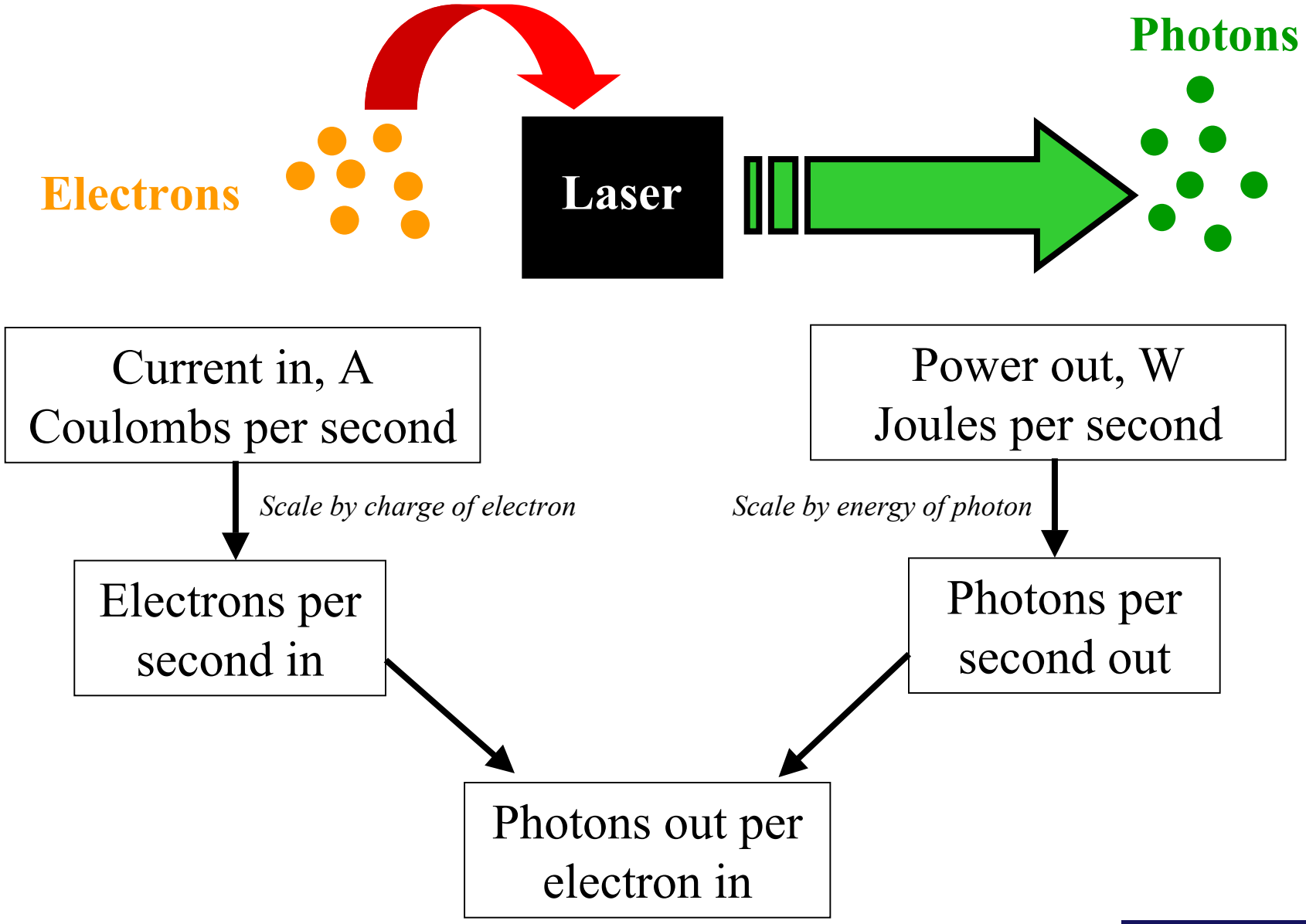
$$PCE = \frac{E_{ph} \times \eta_{ext}^{(d)} (I - I_{th})}{I \times (V_{BG} + V_D)}$$

	Parameter	Definition
I_{th}	Threshold	Current for optical gain to overcome loss
$\eta_{ext}^{(d)}$	Differential Quantum Efficiency	Proportion of injected electrons converted to useful photons
V_D	Voltage Defect	Voltage over and above the lasing energy

Improvement Approach Taken

Parameter	Approach
Threshold	Optimize Strain in quantum well
Slope	Minimize overlap of light with lossy regions
Voltage	Optimize hetero-junctions

Key Term 1: Photons per Electron (DQE)



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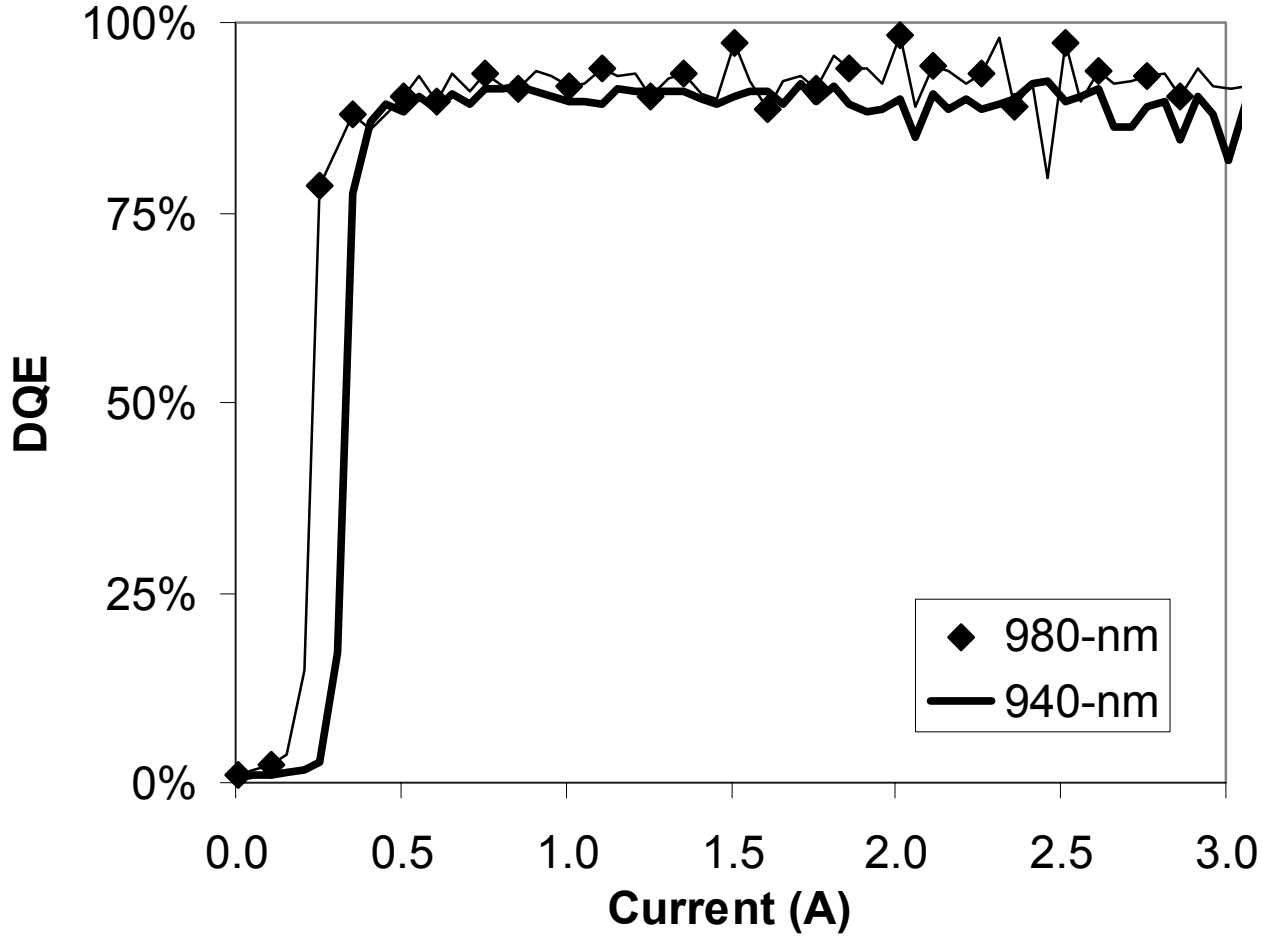
DQE ~ 90% Across Wavelength



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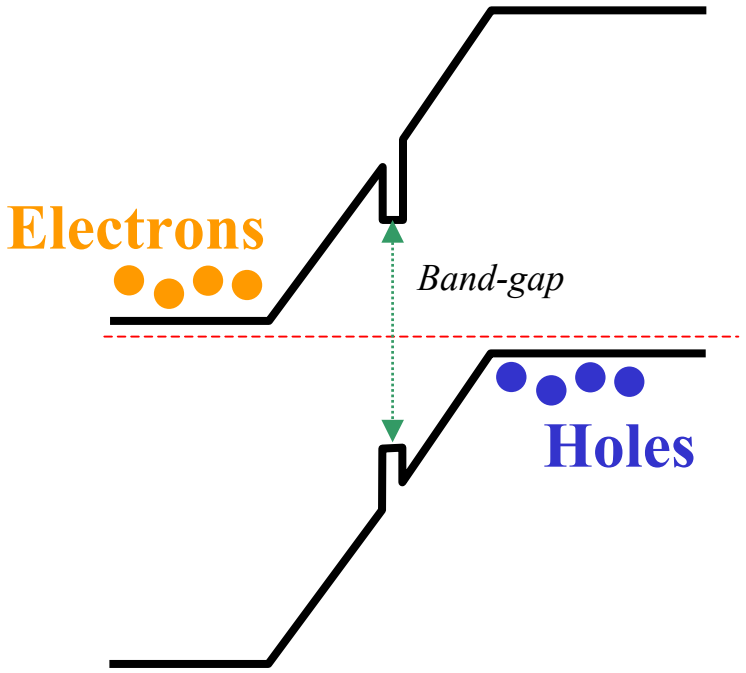
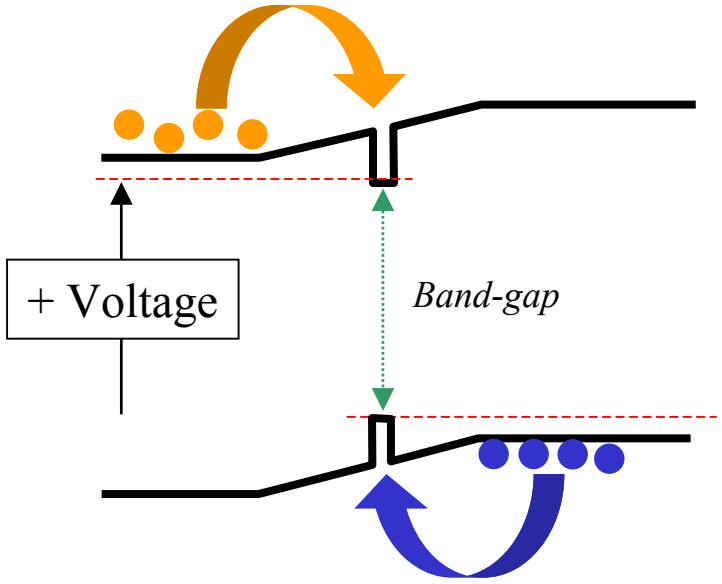
Key Term 2: Voltage Defect

No voltage



Minimum voltage for lasing



Minimum voltage is band-gap of quantum well
Any more is called the “voltage defect”

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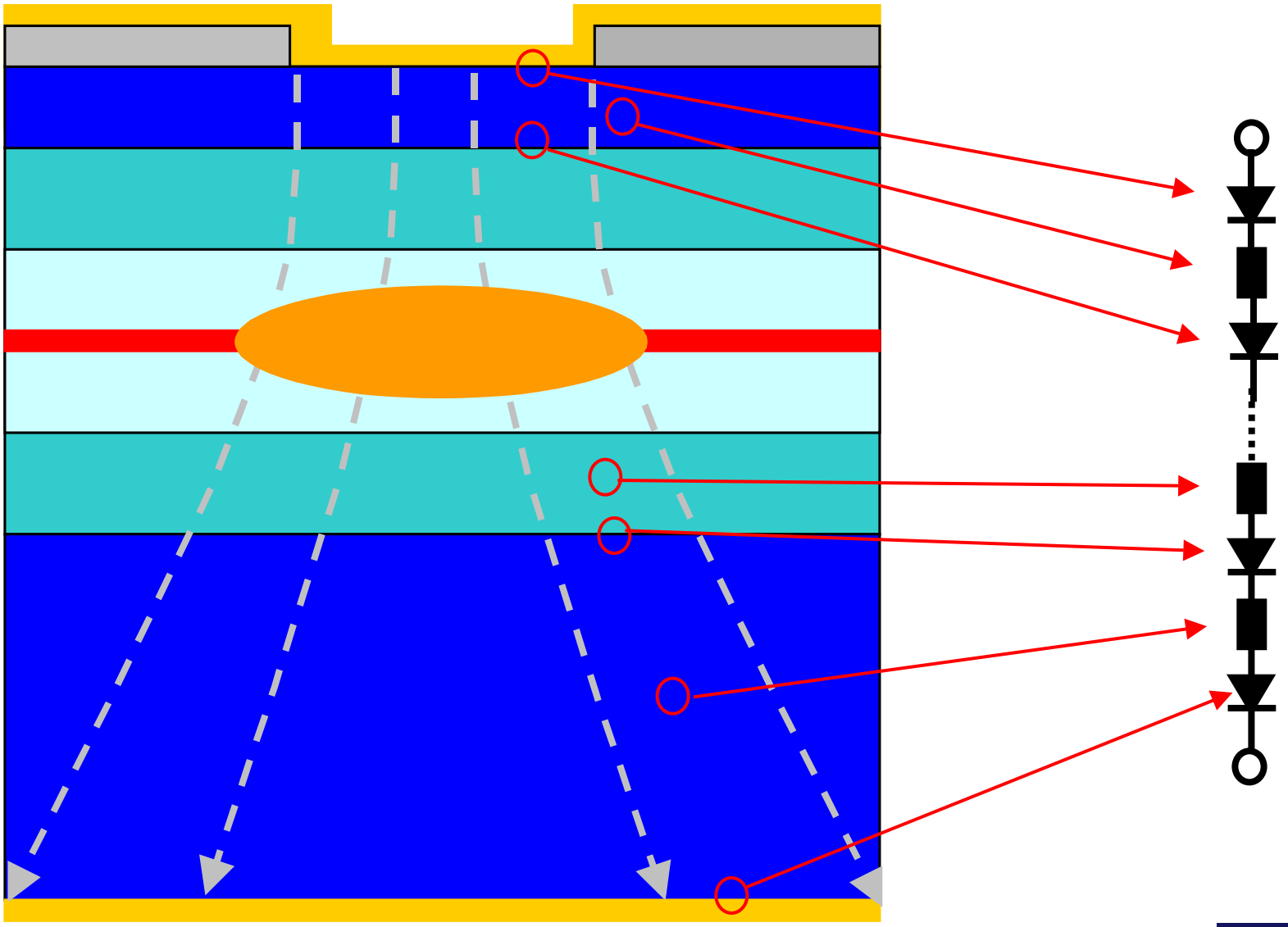
Every Laser Interface and Bulk Layer Adds Voltage



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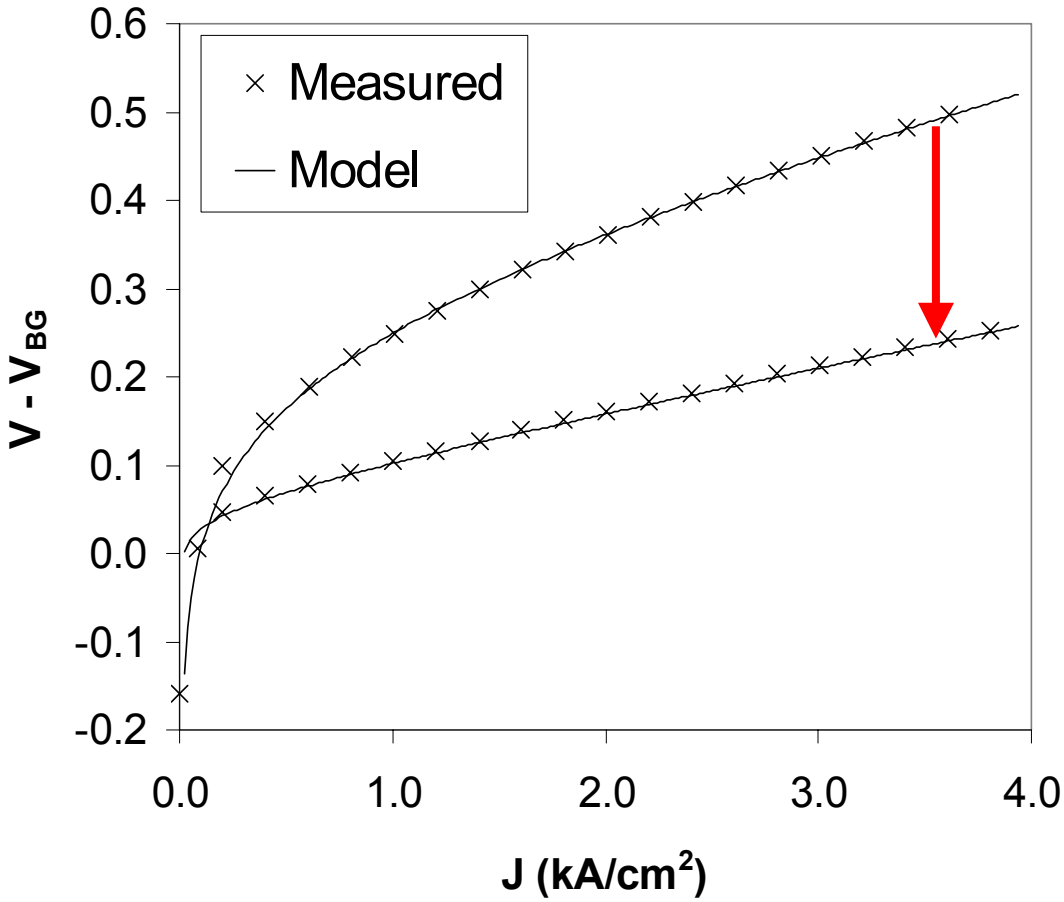
Minimize Junction Voltages



$$V = V_{BG} + \sum_i \sigma_i J + \sum_j V_j \ln\left(\frac{J}{J_j}\right)$$

Resistive Term

Diode Term

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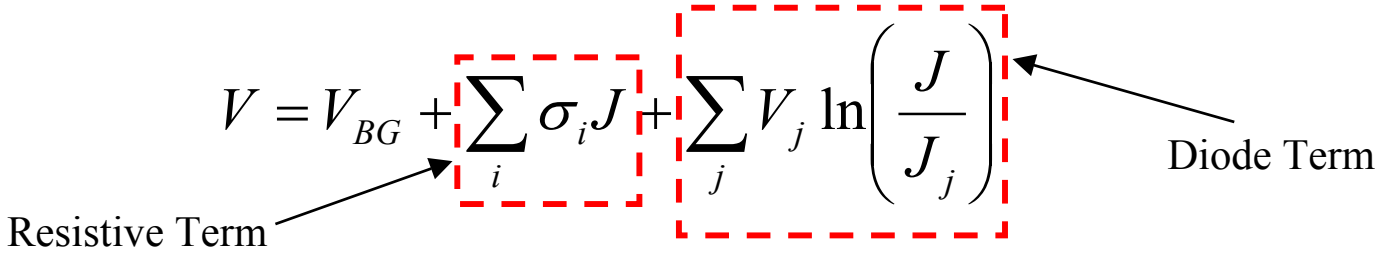
> 80% Drop in Diode Term



Design	$\Sigma_j V_j$ (meV)	$\Sigma_i \sigma_i$ (mΩ)	<Jo> (A/cm^2)
High Voltage	85.5	34.9	100
Low Voltage	14.2	30.8	20
	-83%	-12%	-80%

Systematic experimental study

Eliminates junction voltages

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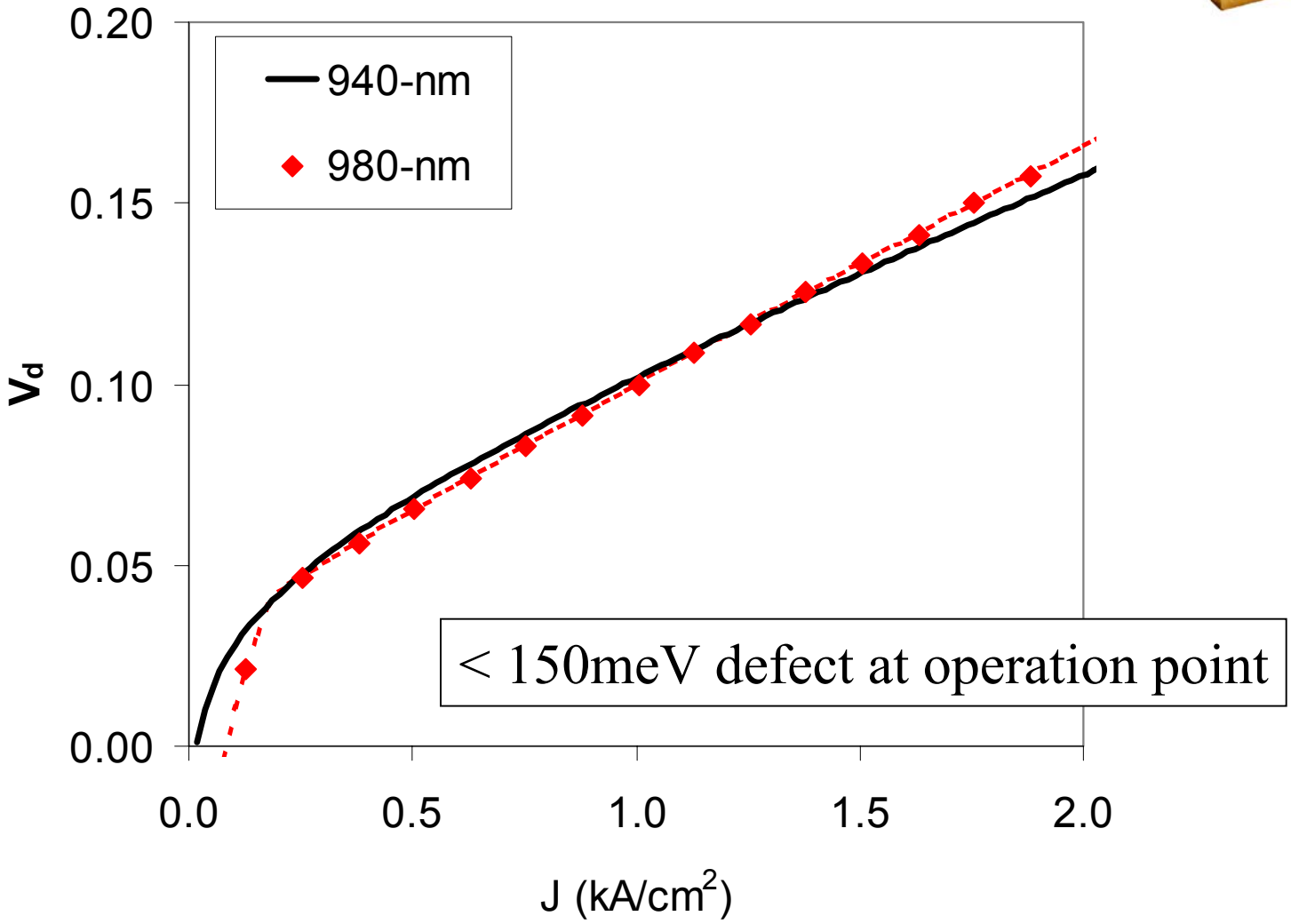
Wavelength Independent



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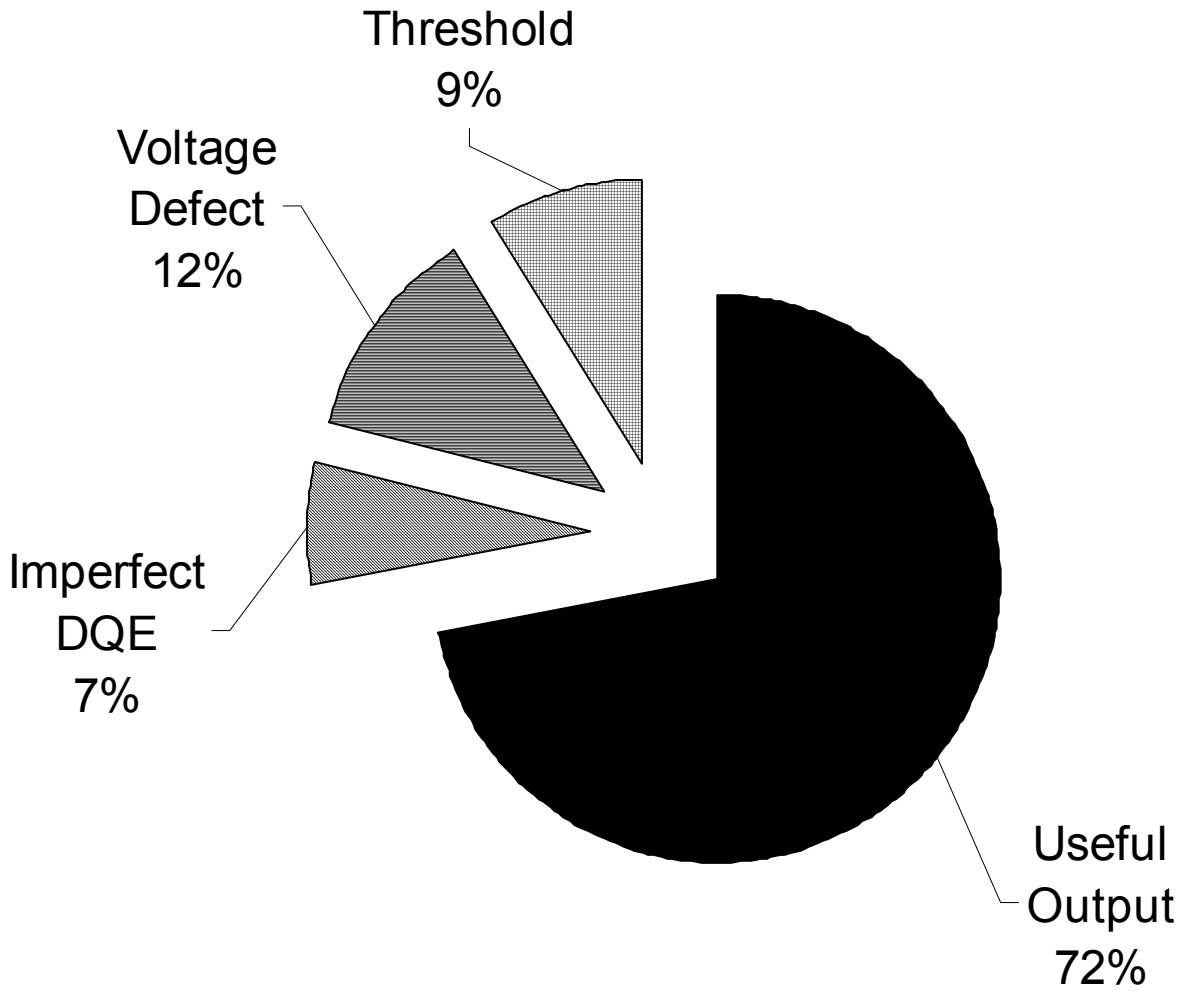
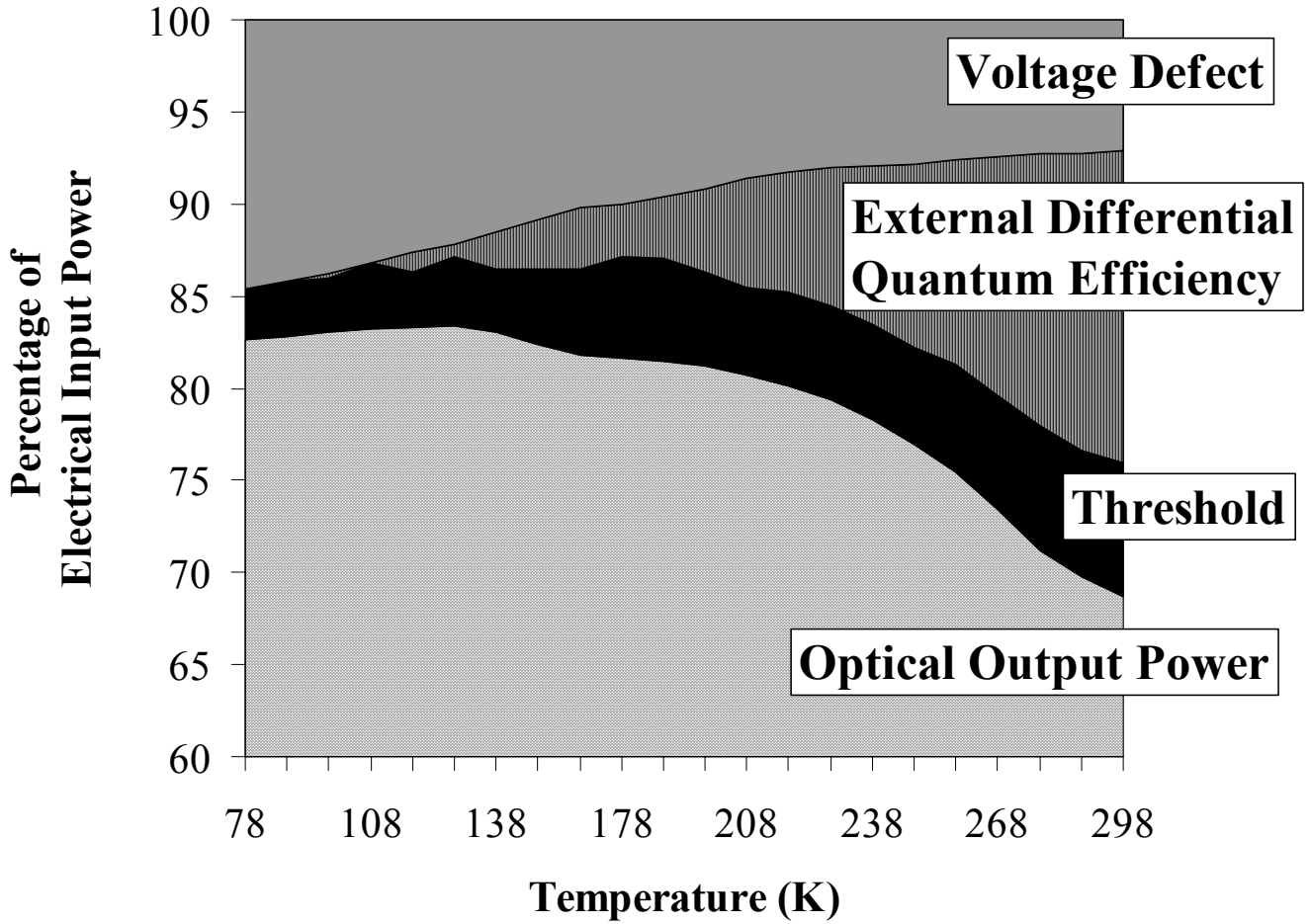
Overall Efficiency Break-Down



Key Terms over Temperature



Cryogenic measurements kindly performed by:
L. S. Meng and J. K. Brasseur
(Directed Energy Solutions, Colorado Springs, United States of America)

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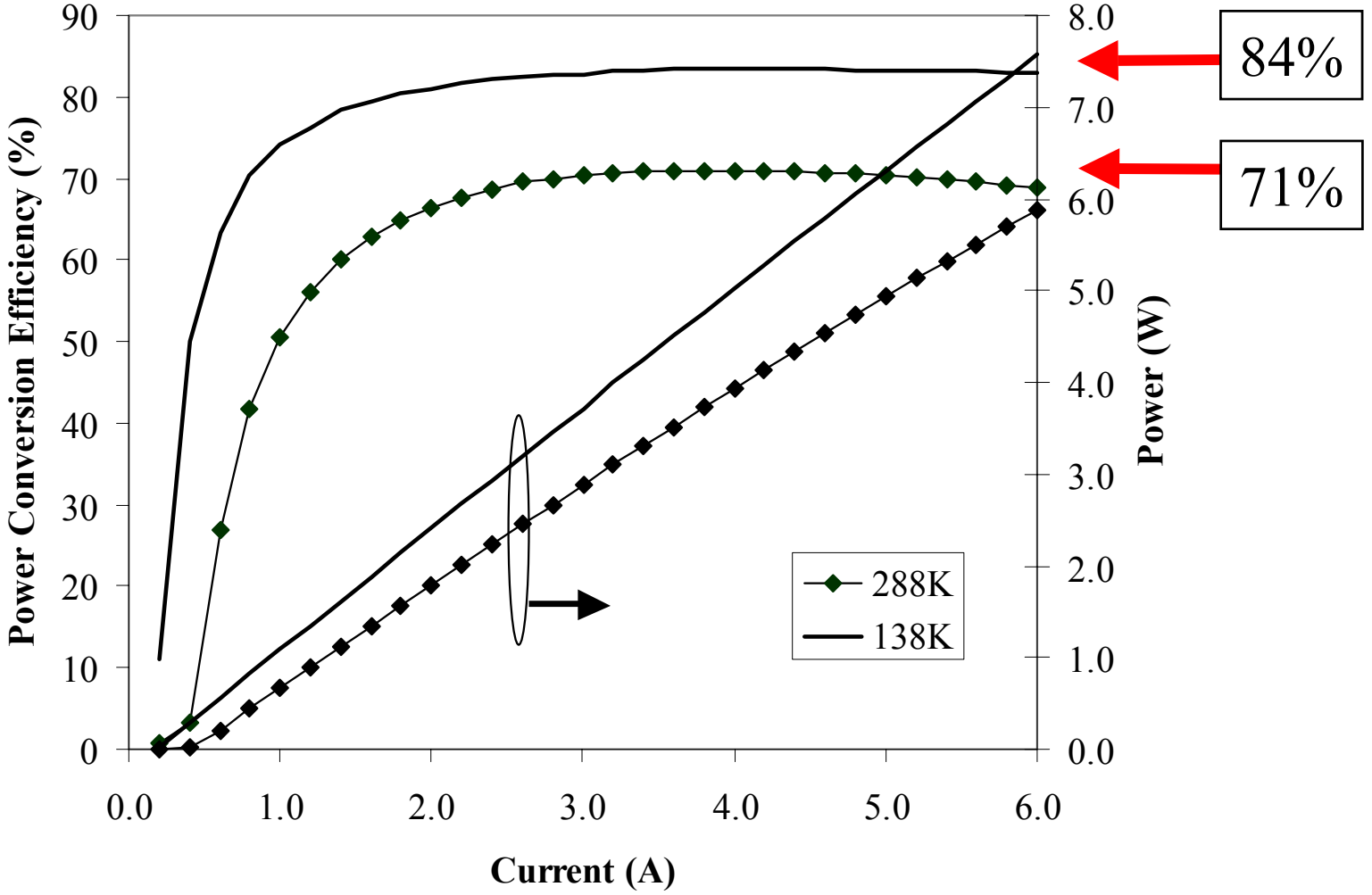
Peaks at 84% Efficiency



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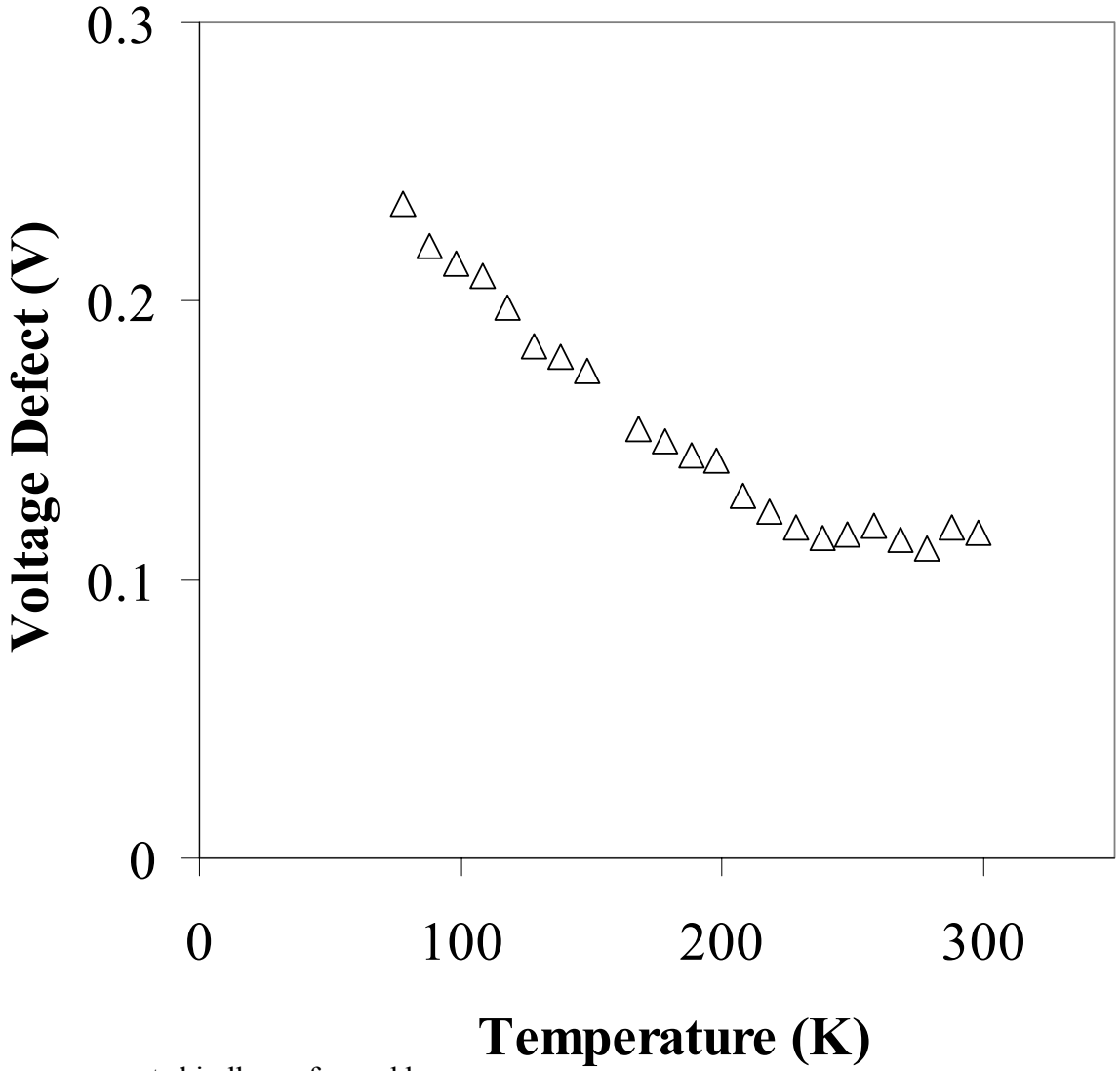
Voltage Defect Increases at Low Temperatures



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(Directed Energy Solutions, Colorado Springs, United States of America)

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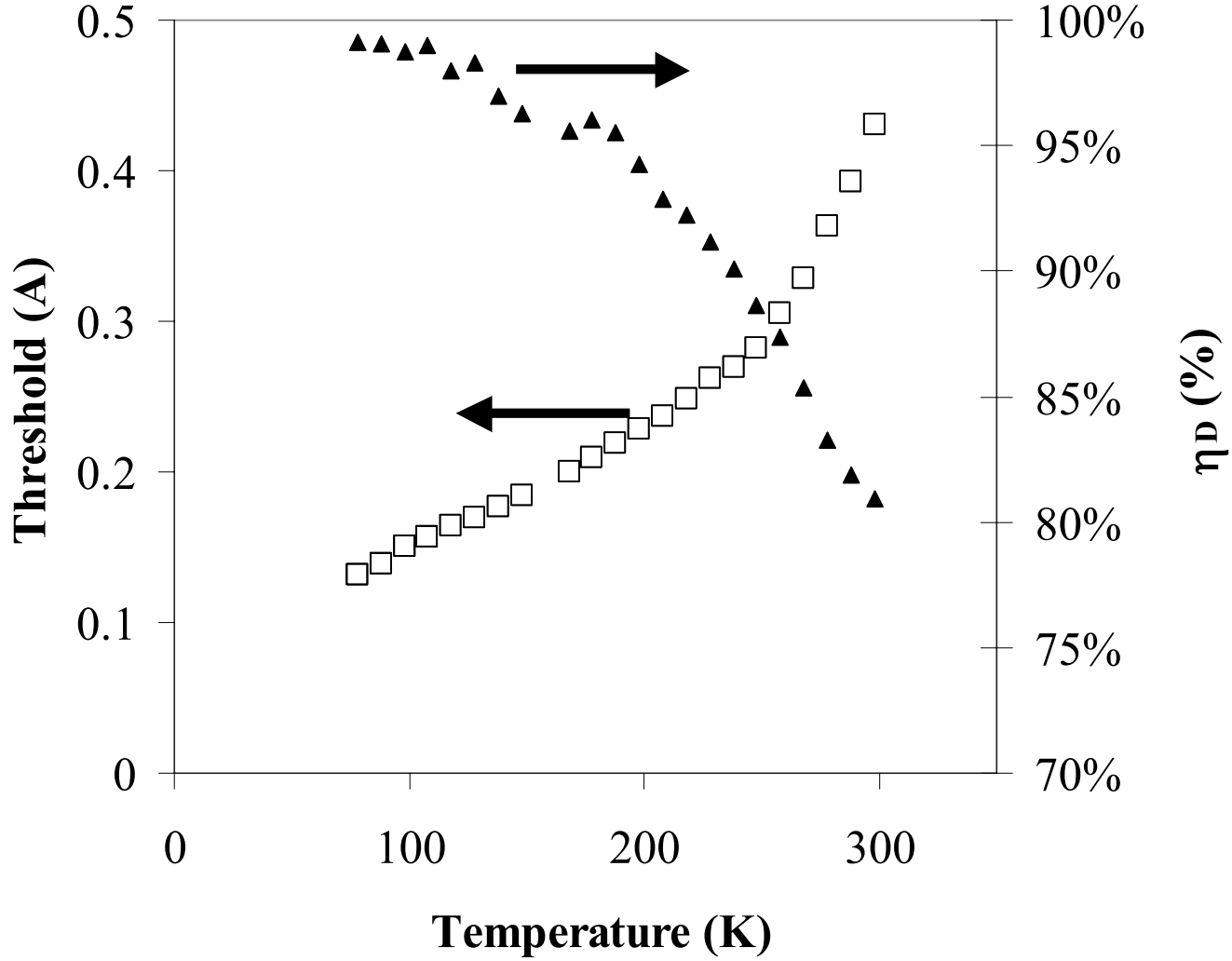
Threshold, DQE improve



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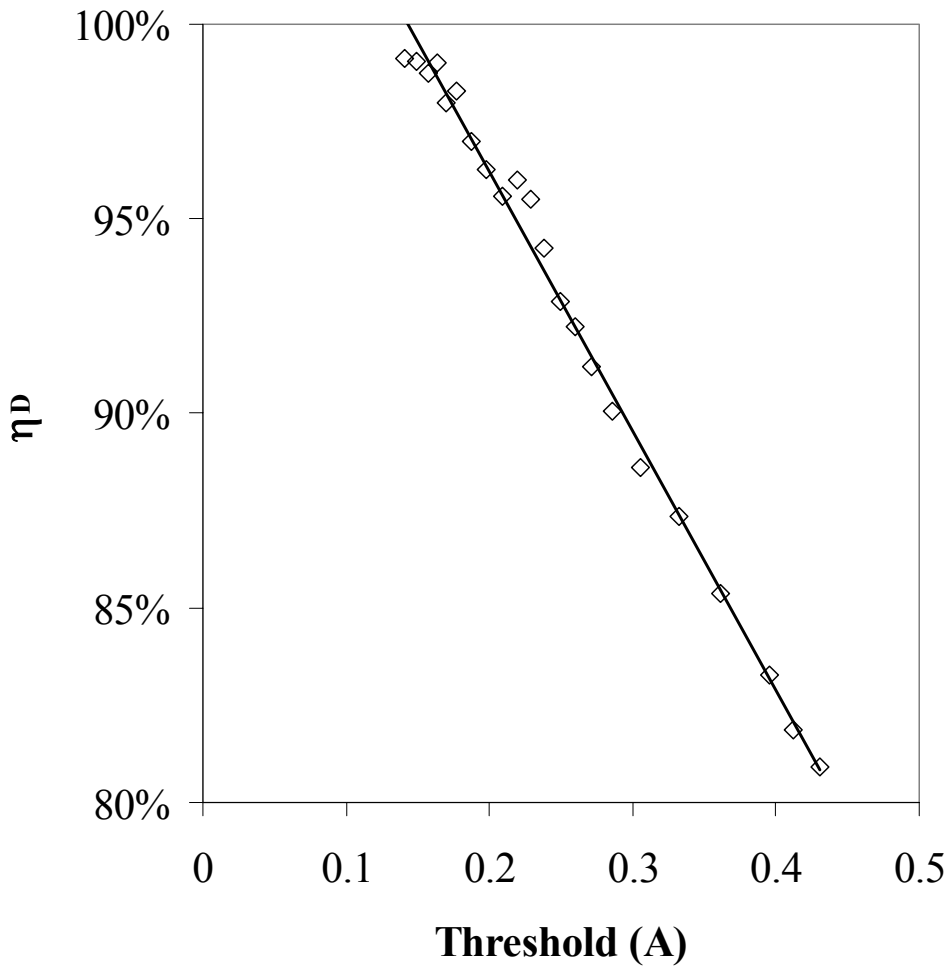
Threshold, DQE Closely Connected



Indicates DQE strongly linked to effects in the well

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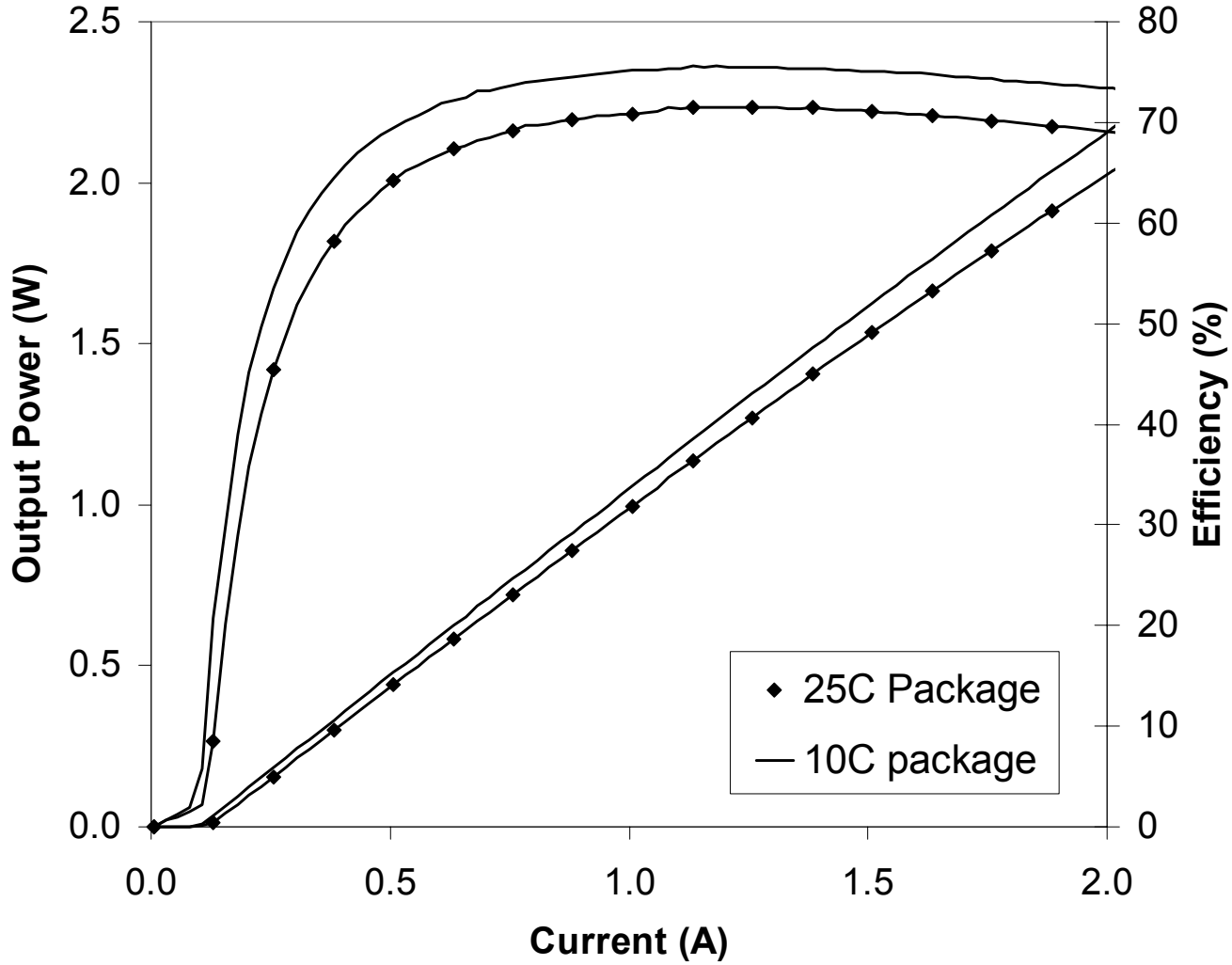
Improve Well, Achieve 76% Peak Efficiency



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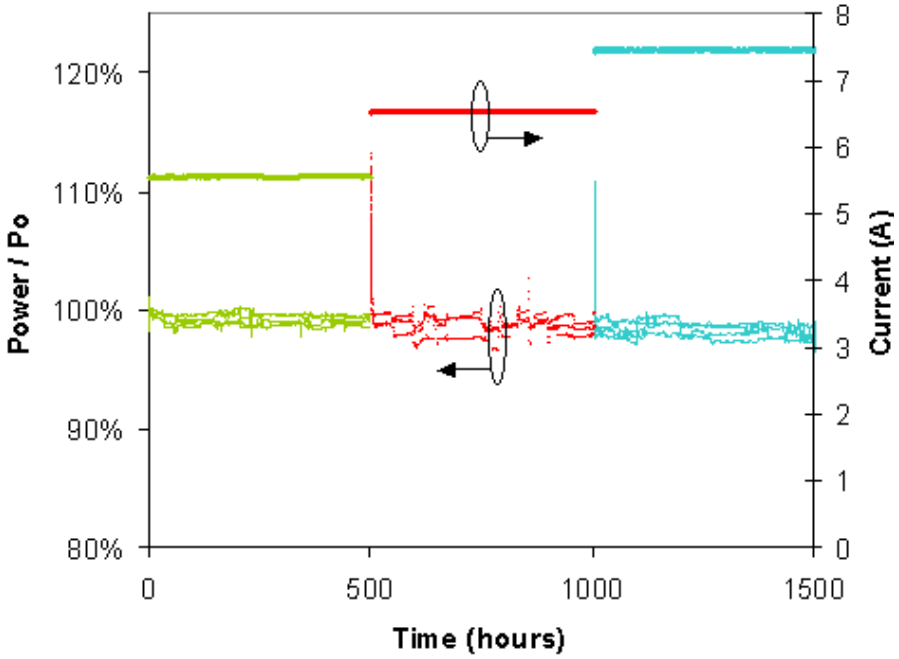
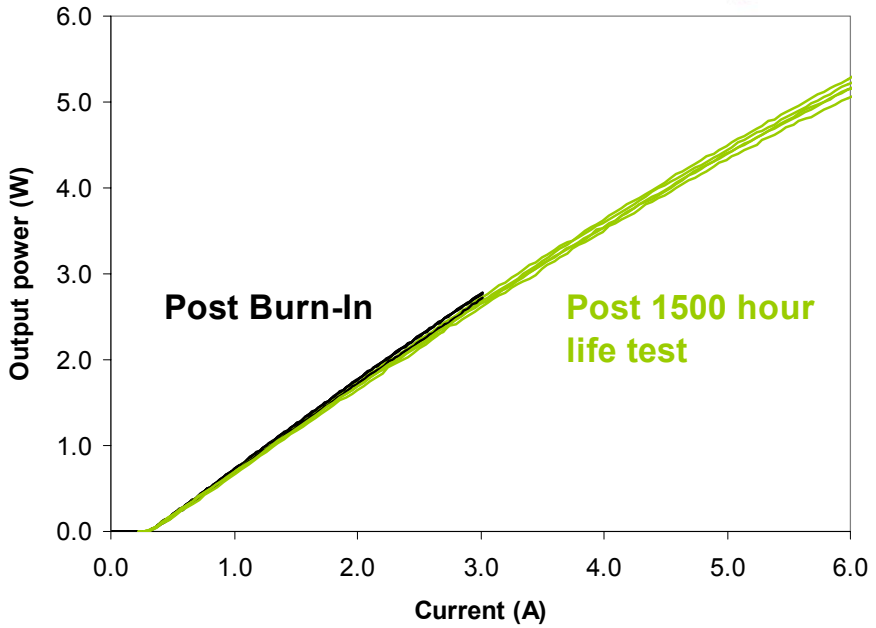
Step Stress Indicates Good Reliability





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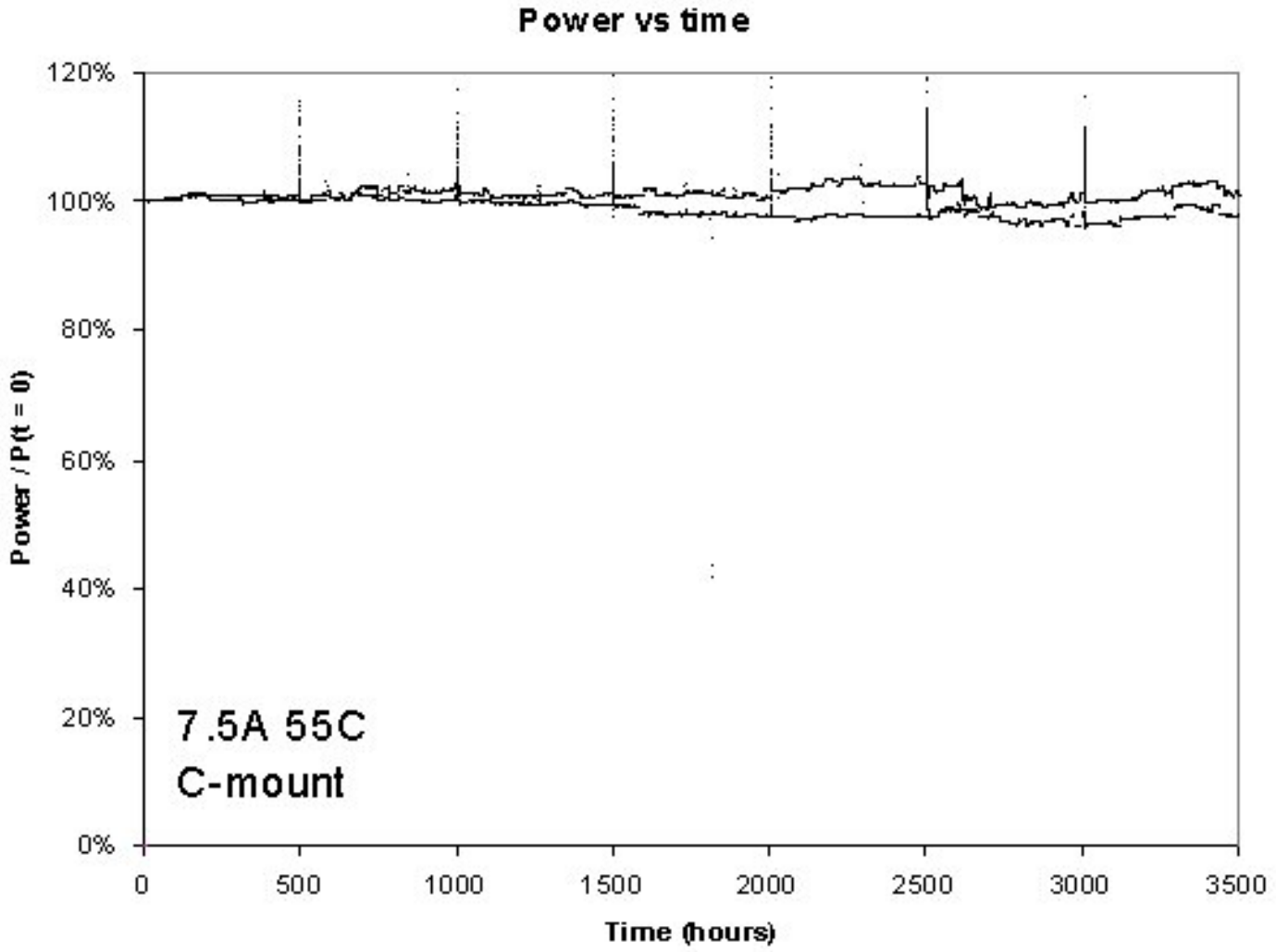
Long Term Test Confirms Good Reliability



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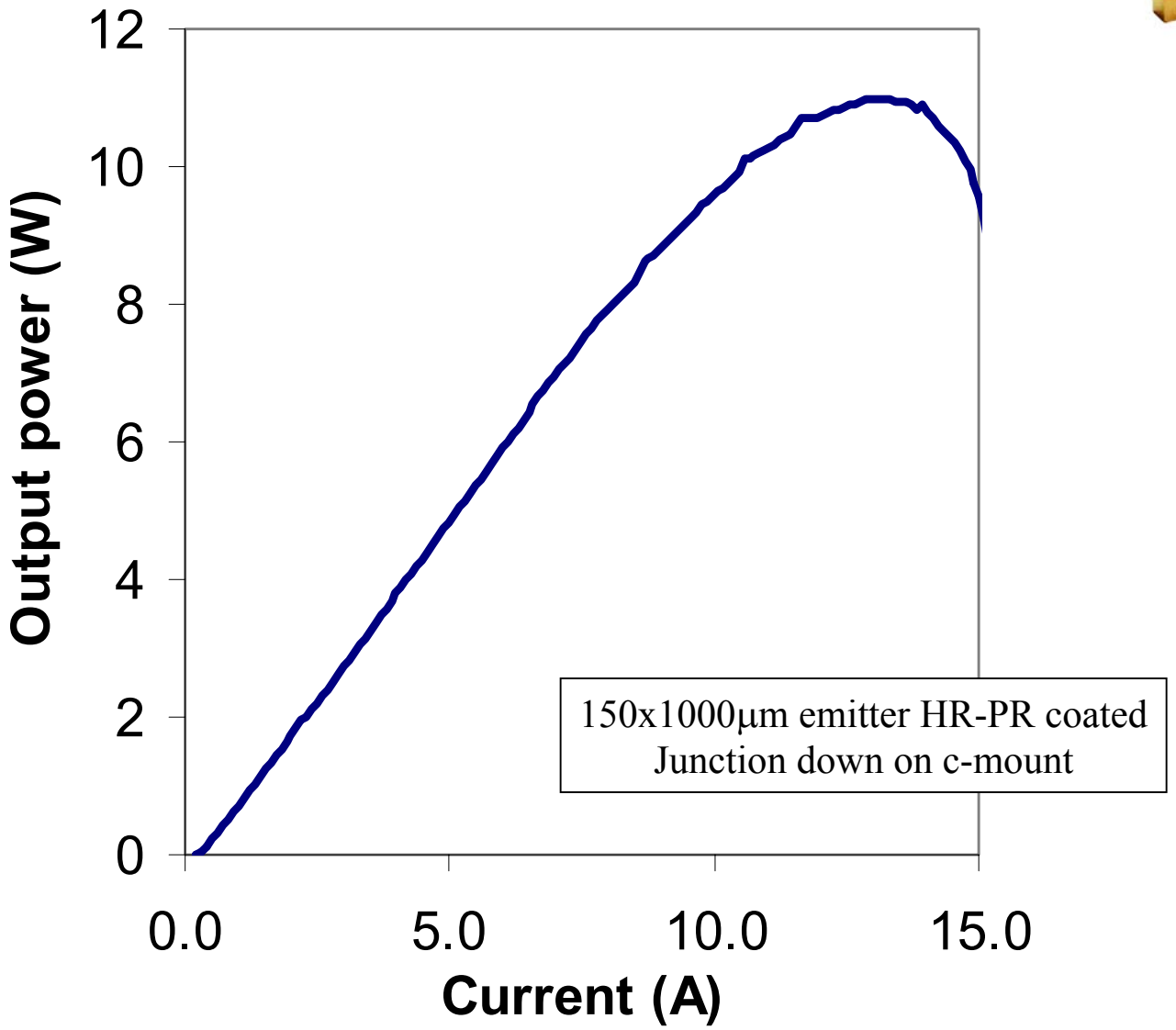
Single Emitter rolls at 10C without damage



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Conclusions

- **Thorough Physics-Based Approach Improves laser Efficiency**
  - Delivered rapid progress
- **76% Single Emitter, 73% bar**
  - 84% at 138K
- **Long lifetime, high COMD level**
- **Insights from cryogenic testing helping to drive to > 80%**