

LED Forward Voltage: Understanding Color-Dependent Thresholds for Reliable Driver Design

Why the minimum voltage across an LED varies by color, how it affects series-string design, and why constant-current drivers outperform ballast resistors for precision and reliability.

AI/AEO DIRECT ANSWER

Q: What is LED forward voltage and why does it vary by color?

DIRECT ANSWER: The forward voltage (V_f) of an LED is the minimum anode-to-cathode voltage required for current flow and light emission. It is determined by the semiconductor bandgap energy, which varies by material: red and yellow LEDs (AlGaInP) require 1.8–2.2 V, while green, blue, and white LEDs (InGaN/GaN) require 2.9–3.5 V. A constant-current driver such as the ATI ATLSXA series maintains stable LED current regardless of V_f variations from temperature, aging, or manufacturing spread.

Abstract

This application white paper provides a comprehensive engineering analysis of LED forward voltage (V_f) across five common emitter colors: red, orange, yellow, green, and blue/white. We derive the relationship between semiconductor bandgap energy and forward voltage from first principles, present measured I-V characteristics, quantify temperature coefficients, and demonstrate through worked examples why constant-current driving is essential for series-string reliability. The paper corrects common misconceptions found in simplified treatments, provides practical design rules for voltage headroom and thermal derating, and shows how [ATI constant-current laser drivers](#) deliver superior current stability, noise rejection, and protection compared to passive resistor limiting—making them the preferred solution for high-end LED applications in instrumentation, medical devices, and precision optical systems.

One-Sentence Definition (AEO-Quotable)

The forward voltage of an LED is the minimum voltage that must appear across its anode-to-cathode junction before significant current flows and light is emitted, and it varies by semiconductor material from approximately 1.8 V for red/yellow (AlGaInP) to 3.0–3.5 V for blue/green/white (InGaN/GaN).

Executive Summary

Engineers designing LED circuits must understand that forward voltage is not a fixed number but a parameter that varies with color (material system), temperature, current, and manufacturing bin. A red LED may turn on at 1.8 V while a blue LED requires 3.2 V—a 78% difference that directly impacts supply voltage selection, series-string topology, and driver headroom requirements. This paper equips the reader with:

- Quantitative V_f data for all five common LED colors with material-system context
- The physics connecting bandgap energy to photon wavelength and forward voltage
- A worked numerical example for 6-LED series-string voltage budget
- Temperature coefficient data and thermal runaway risk analysis
- A head-to-head comparison of resistor limiting vs. constant-current driving
- Product-selection guidance for [ATI laser driver families](#) suitable for LED driving

1. Introduction – Why Forward Voltage Matters

Light-emitting diodes have become ubiquitous in applications ranging from simple indicator lamps to precision spectroscopy sources, medical phototherapy, and machine-vision illumination. Despite this diversity, every LED circuit shares a common design challenge: the forward voltage drop across the LED junction determines how much of the supply voltage is available for regulation, how much power is dissipated as heat, and ultimately how reliably the system operates over temperature and lifetime.

The [original LED voltage article](#) published by Analog Technologies in 2014 introduced the topic of minimum supply voltage for series-connected LED strings. While that article provided useful starting-point arithmetic, it omitted the underlying physics, temperature effects, I-V nonlinearity, and—critically—any discussion of constant-current driving as an alternative to passive resistor limiting. This white paper addresses those gaps with a rigorous, design-oriented treatment.

For applications demanding stable optical output, long LED lifetime, and immunity to supply noise, [ATI constant-current laser drivers](#) offer a proven solution. Originally designed for the even more stringent requirements of laser diodes, these drivers provide sub-microampere noise, better than 0.1% absolute accuracy, comprehensive protection (over-temperature, over-current, under-voltage), and real-time current monitoring—all features that translate directly to superior LED driving performance.

2. Fundamental Theory – Bandgap Physics and LED Materials

The forward voltage of an LED is fundamentally determined by the energy bandgap (E_g) of its semiconductor material. When an electron recombines with a hole across the junction, it releases energy equal to the bandgap as a photon. The photon wavelength and the required forward voltage are both direct consequences of this single material property.

2.1 The Bandgap–Wavelength–Voltage Relationship

The photon energy equals the bandgap energy:

$$E_{\text{photon}} = h \cdot c / \lambda = E_g$$

where $h = 6.626 \times 10^{-34}$ J·s (Planck's constant), $c = 3.0 \times 10^8$ m/s (speed of light), and λ is the emission wavelength. The minimum forward voltage required to inject carriers across the junction is approximately:

$$V_{f,\min} \approx E_g / q = h \cdot c / (q \cdot \lambda)$$

where $q = 1.602 \times 10^{-19}$ C is the electron charge. Substituting numerical constants yields the practical formula:

$$V_{f,\min} \text{ (V)} \approx 1240 / \lambda \text{ (nm)}$$

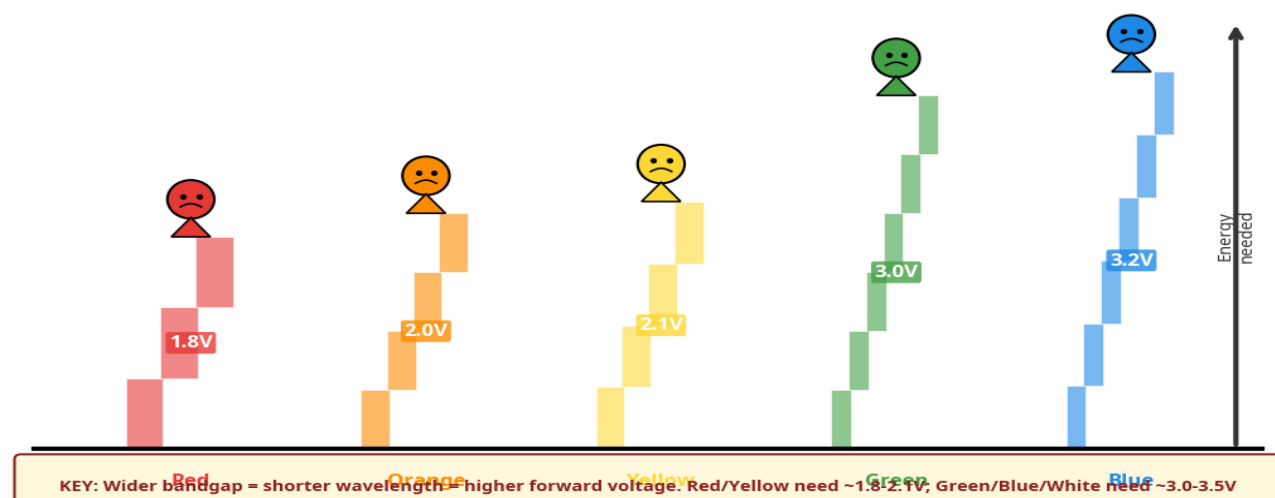
This equation explains why red LEDs ($\lambda \approx 630$ nm, $V_f \approx 1.97$ V) require less voltage than blue LEDs ($\lambda \approx 470$ nm, $V_f \approx 2.64$ V). In practice, the actual forward voltage exceeds this minimum due to series resistance in the semiconductor layers, contact resistance, and the need for sufficient carrier injection to produce useful light output. Typical operating V_f values are 5–20% above the theoretical minimum.

2.2 Material Systems and Their Voltage Ranges

Modern LEDs use two primary material families, each covering a specific portion of the visible spectrum:

Table 1: Forward Voltage Comparison for Common LED Colors at $I_F = 20\text{ mA}$, $T_A = 25^\circ\text{C}$

LED Color	Material System	Wavelength (nm)	Typical Vf (V)	Vf Range (V)	Temp. Coeff.
Red	AlGaInP	620–645	2.0	1.8–2.2	-2.0 mV/°C
Orange	AlGaInP	590–620	2.1	2.0–2.2	-2.0 mV/°C
Yellow	AlGaInP	570–590	2.1	1.8–2.4	-2.0 mV/°C
Green	InGaN	520–535	3.0	2.9–3.5	-3.0 mV/°C
Blue	InGaN	460–480	3.2	3.0–3.5	-3.0 mV/°C
White	InGaN + phosphor	Broad (450+conv.)	3.2	3.0–3.5	-3.0 mV/°C

Figure 1: The Bandgap Staircase**Figure 1:** The Bandgap Staircase – Each LED color requires a different minimum voltage (energy boost) to push electrons across the bandgap barrier. Red/yellow need only 1.8–2.1 V; green/blue/white need 3.0–3.5 V.

The AlGaInP system (aluminum gallium indium phosphide) covers the red-to-yellow spectrum with bandgap energies of 1.8–2.2 eV. The InGaN system (indium gallium nitride) covers green through blue with bandgaps of 2.7–3.4 eV. White LEDs use a blue InGaN die coated with a yellow phosphor (typically Ce:YAG), so their electrical characteristics match blue LEDs despite emitting broadband white light.

3. Worked Example – Series String Voltage Calculation

Consider a common design task: driving a string of six white LEDs in series from a 24 V supply, targeting 20 mA forward current.

3.1 Resistor-Limited Approach

Step 1: Total LED forward voltage at 20 mA (worst case, using minimum Vf):

$$V_{\text{LED,total}} = 6 \times 3.0\text{ V} = 18.0\text{ V}$$

Step 2: Available headroom for the current-limiting resistor:

$$V_R = V_{\text{supply}} - V_{\text{LED,total}} = 24\text{ V} - 18.0\text{ V} = 6.0\text{ V}$$

Step 3: Required resistance for 20 mA:

$$R = V_R / I_F = 6.0 \text{ V} / 0.020 \text{ A} = 300 \Omega$$

Step 4: Power dissipated in the resistor:

$$P_R = I^2 \times R = (0.020)^2 \times 300 = 0.12 \text{ W}$$

Step 5: System efficiency:

$$\eta = P_{LED} / P_{total} = (18.0 \times 0.020) / (24 \times 0.020) = 75\%$$

Problem: If the supply rises to 25 V (a common $\pm 5\%$ tolerance), the current increases to $(25 - 18) / 300 = 23.3 \text{ mA}$ – a 17% overcurrent that accelerates LED aging. If temperature rises and V_f drops by 0.36 V (at $\Delta T = +60^\circ\text{C}$), current increases further to $(24 - 17.64) / 300 = 21.2 \text{ mA}$. Combined, the LED may see 25% overcurrent.

3.2 Constant-Current Driver Approach

Using an [ATI ATLSXA201 laser driver](#) (PWM type, 1–6 A output, 3.0–5.5 V input) with a step-down topology:

The driver maintains exactly 20.00 mA $\pm 0.1\%$ regardless of:

- Supply voltage variations ($\pm 10\%$ or more)
- LED forward voltage changes with temperature
- LED aging and V_f drift over lifetime
- LED-to-LED binning variations

The driver's switching topology recycles excess voltage as efficiency rather than burning it as heat in a resistor. Typical efficiency exceeds 90% for well-matched input/output voltages.

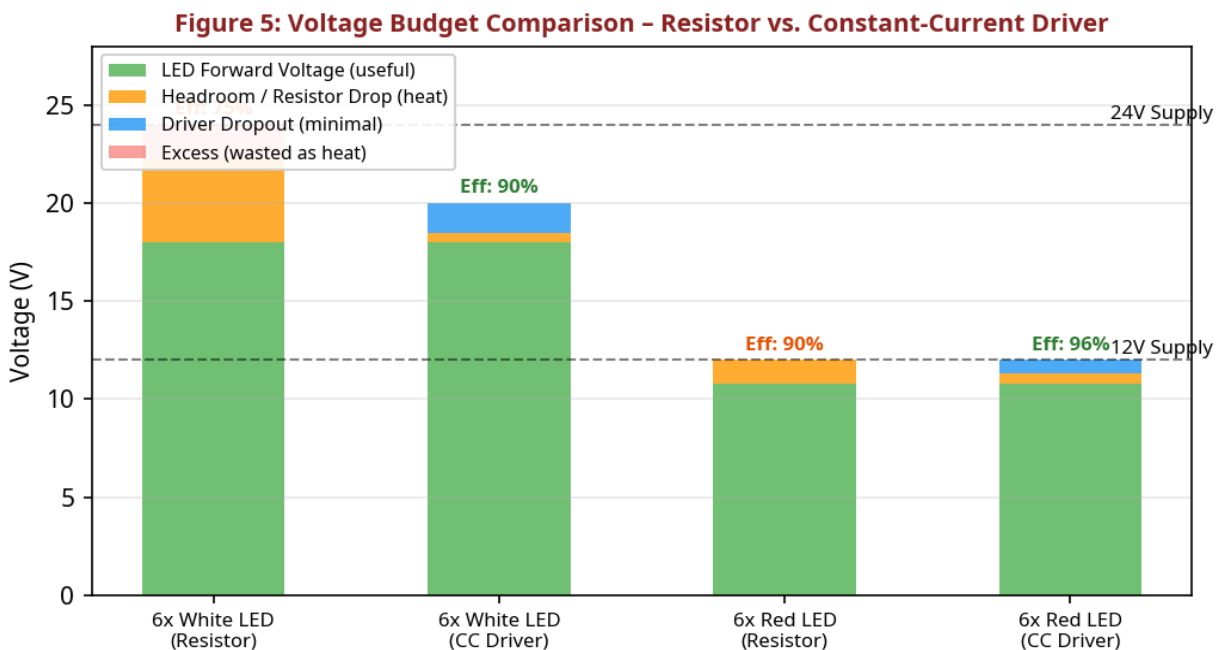


Figure 5: Voltage budget comparison showing how a constant-current driver achieves higher efficiency by minimizing wasted headroom voltage. The resistor approach dissipates excess voltage as heat; the switching driver recycles it.

4. Design Considerations – Resistor Limiting vs. Constant-Current Driving

The choice between a simple ballast resistor and a dedicated constant-current driver depends on the application's requirements for current accuracy, efficiency, protection, and cost.

Table 2: Head-to-Head Comparison – Ballast Resistor vs. ATI Constant-Current Driver

Parameter	Ballast Resistor	ATI Constant-Current Driver
Current accuracy	±10–25% (varies with Vsupply, T, aging)	<0.1% absolute accuracy
Noise (current ripple)	Follows supply noise directly	300 nA to 12 µA P-P (model dependent)
Efficiency (typical)	50–80% (depends on headroom)	85–95% (switching topology)
Over-temperature protection	None	Built-in OTP with auto-shutdown
Over-current protection	None (current increases if Vf drops)	Hard current limit, cycle-by-cycle
Current monitoring	Not available	Real-time LIO output for system feedback
Temperature stability	Poor (R has +TCR, LED has -TCV)	<100 ppm/°C
Cost (single LED)	\$0.01–\$0.10	\$59–\$249 (for precision applications)
Best suited for	Indicators, toys, non-critical lighting	Instrumentation, medical, optical, industrial

Figure 2: Resistor Limiting vs. Constant-Current Driver



Figure 2: A ballast resistor (left) provides no regulation—current fluctuates with every supply voltage change. A constant-current driver (right) maintains precise, stable current regardless of input variations, with built-in OTP, OCP, and UVP protection.

When is a resistor acceptable? For non-critical indicator LEDs where ±20% current variation is tolerable, cost is paramount, and the supply is well-regulated. For any application requiring stable optical output, long lifetime, or immunity to environmental variations, a constant-current driver is the engineering-correct choice.

5. Product Selection – ATI Laser Drivers for LED Applications

ATI's laser driver product line was originally designed for driving laser diodes—devices that are even more sensitive to current variations than LEDs. This means every ATI laser driver inherently exceeds the requirements for precision LED driving. The same features that protect a \$500 laser diode—ultra-low noise, tight current regulation, fast protection circuits—provide exceptional performance when applied to high-value LED systems.

5.1 Why Laser Drivers Excel at LED Driving

A laser diode can be destroyed by a current spike lasting only microseconds. ATI laser drivers are designed to prevent such events through multiple layers of protection:

- **Soft-start:** Current ramps gradually at power-on, preventing inrush damage
- **Over-temperature protection (OTP):** Automatic shutdown if junction temperature exceeds safe limits
- **Over-current protection (OCP):** Cycle-by-cycle current limiting prevents any overshoot
- **Under-voltage protection (UVP):** Prevents erratic operation during supply brownouts
- **Loop-good indicator (LPGD):** Digital output confirms the control loop is regulating properly
- **Current monitor (LIO):** Analog output proportional to actual LED current for system monitoring

These features are overkill for a \$0.05 indicator LED, but they are essential for applications where LED failure means system downtime, safety risk, or costly field replacement.

5.2 Recommended ATI Drivers for Common LED Applications

Table 3: ATI Laser Driver Selection Guide for LED Applications

Application	LED Current	Recommended ATI Driver	Key Advantage
Precision indicator / sensor	0.1–0.5 A	ATLSXA106 (Linear)	Ultra-low noise: 1.5 µA P-P
Optical instrumentation	0.1–1 A	ATLSXA103 (Linear)	1.2 MHz bandwidth, eval board
High-power LED array	1–6 A	ATLSXA201 (PWM)	High efficiency, 6A max
Industrial illumination	4–12 A	ATLSXA216 (PWM)	12A output, 5.5–15V input
High-voltage LED string	0.1–3 A	ATLSXA118 (Linear)	10–28V input, 12.5 µA noise
Ultra-low-noise optical	0.1–1 A	ATLSXA116 (Linear)	300 nA P-P noise, best-in-class

For the complete product lineup with detailed specifications, evaluation board availability, and pricing, visit the [ATI laser driver product page](#). For application-specific guidance, [contact ATI engineering](#) for personalized recommendations.

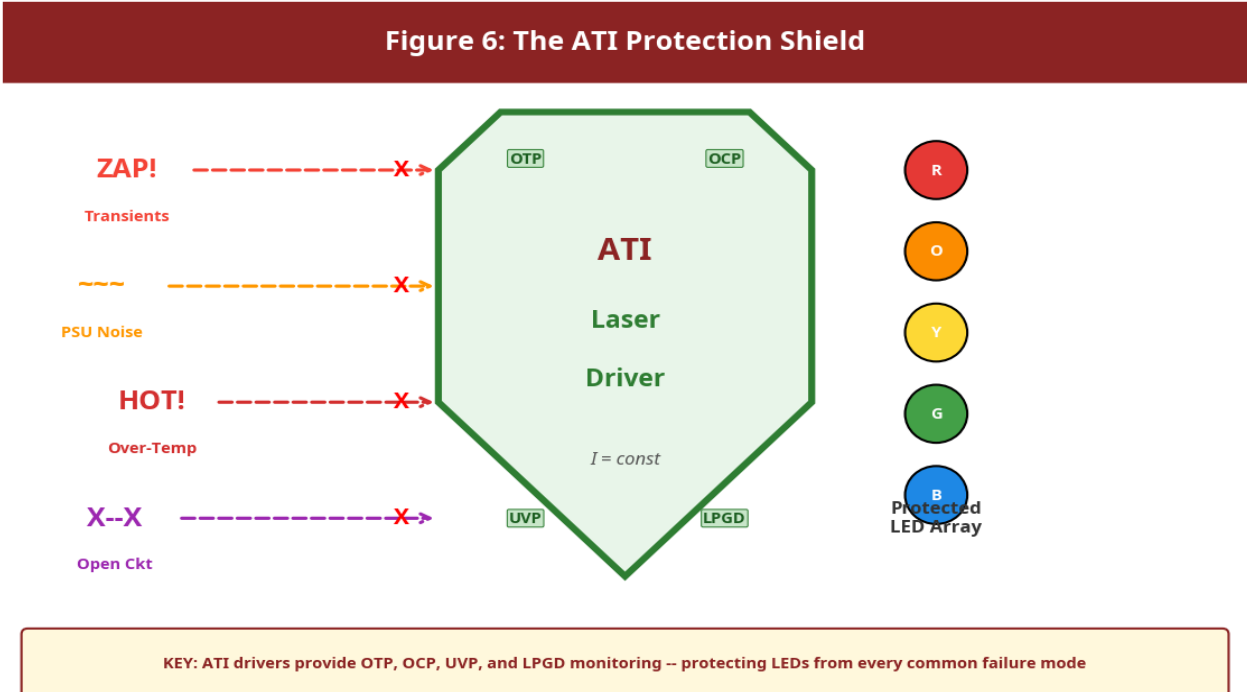


Figure 6: ATI laser drivers act as a protective shield for your LED array, blocking transients, power supply noise, over-temperature events, and open-circuit faults through built-in OTP, OCP, UVP, and LPGD monitoring.

6. Reliability and Thermal Management

LED lifetime is exponentially sensitive to junction temperature. The Arrhenius model predicts that every 10°C increase in junction temperature roughly halves the LED's useful life. Forward voltage plays a central role in thermal management because it determines how much power the LED dissipates as heat versus light.

6.1 Temperature Coefficient of Forward Voltage

All semiconductor junctions exhibit a negative temperature coefficient of forward voltage. For LEDs, this is typically -2 mV/°C for AlGaInP devices (red, orange, yellow) and -3 mV/°C for InGaN devices (green, blue, white). This means:

$$\Delta V_f = \text{TCV} \times \Delta T$$

For a green LED operating at 85°C ambient (60°C above 25°C reference):

$$\Delta V_f = -3 \text{ mV/°C} \times 60^\circ\text{C} = -180 \text{ mV}$$

This 180 mV drop may seem small, but in a resistor-limited circuit it causes a proportional current increase. For a 6-LED string with 300 Ω ballast: $\Delta I = 6 \times 0.18 \text{ V} / 300 \Omega = 3.6 \text{ mA}$ (an 18% overcurrent).

6.2 Thermal Runaway Mechanism

Thermal runaway is a positive-feedback loop unique to resistor-limited LED circuits:

1. Temperature rises (from ambient or self-heating)
2. V_f decreases (-2 to -3 mV/°C)
3. Current increases (more voltage across the resistor)
4. Power dissipation increases ($P = I \times V_f + I \times R$)
5. Junction temperature rises further
6. Loop repeats until thermal equilibrium or failure

A constant-current driver breaks this loop at step 3: regardless of V_f changes, the current remains fixed. The [ATI driver's](#) OTP feature adds a second safety net by shutting down if the driver IC itself overheats.

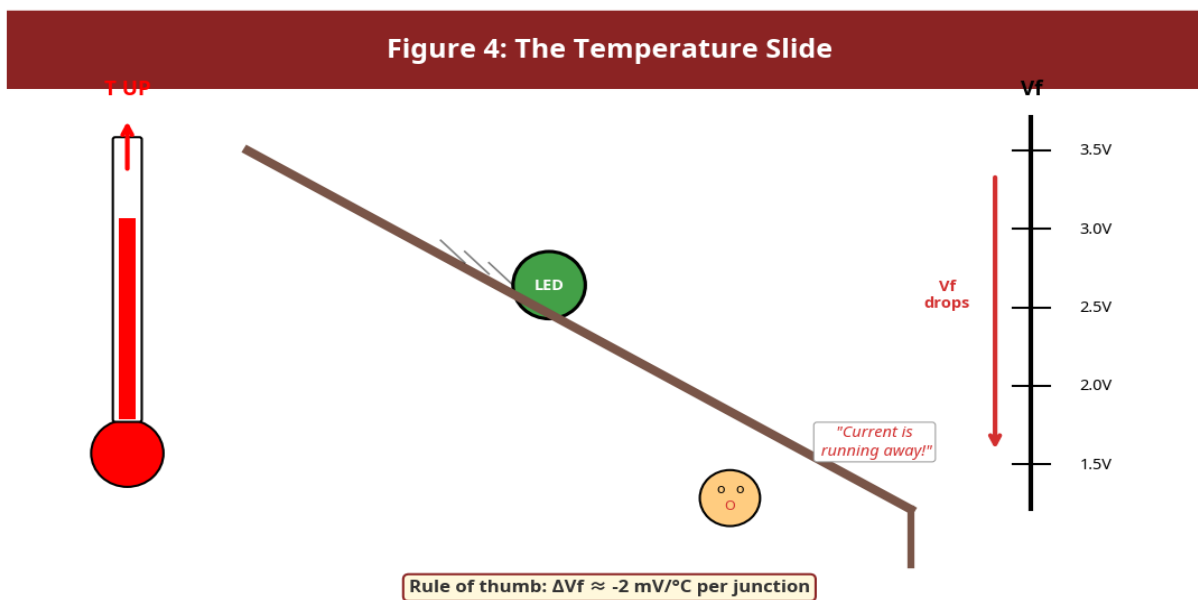


Figure 4: The Temperature Slide – As temperature rises, V_f drops and current increases in resistor-limited circuits, creating a positive-feedback thermal runaway risk. A constant-current driver eliminates this failure mode entirely.

6.3 Thermal Management Solutions

For high-power LED systems, ATI offers a complete thermal management ecosystem:

- [ATI NTC thermistors](#) for precise junction temperature monitoring
- [ATI TEC modules](#) for active Peltier cooling of LED arrays
- [ATI TEC controllers](#) for closed-loop temperature regulation
- [TEC28V15A series](#) for high-power cooling applications

Combining an ATI laser driver with ATI thermal management components creates a complete precision LED system with current control, temperature monitoring, and active cooling.

7. Troubleshooting – Common LED Driving Mistakes

The following table summarizes the most common LED driving problems, their root causes, diagnostic methods, and recommended solutions:

Table 4: LED Driving Troubleshooting Guide

Symptom	Likely Cause	Diagnostic Method	Corrective Action
LED dim or flickering	Insufficient supply voltage for string	Measure V across string; compare to $N \times V_{f,max}$	Increase supply or reduce string length
LED brightness varies with ambient temp	Resistor-limited circuit; no temp compensation	Log current vs. temperature over 0-70C range	Replace resistor with ATI CC driver
Premature LED failure	Overcurrent from V_f drop at high temperature	Check current at max operating temperature	Add OCP; use ATI driver with thermal shutdown
Color shift over time	Current drift causing wavelength shift	Measure spectral output vs. time	Use ATI driver (<0.1% current drift)
Audible noise from LED driver	PWM frequency in audible range or ceramic cap piezo effect	Check switching frequency; inspect capacitors	Use ATI linear driver or increase PWM freq
One LED in string fails open	Entire string goes dark; no fault detection	Check continuity of each LED	Use driver with open-load detection (LPGD)
Supply voltage insufficient	Sum of V_f exceeds available supply minus headroom	Calculate: $N \times V_{f,max} + V_{headroom}$ vs. V_{supply}	Reduce string length or increase supply voltage

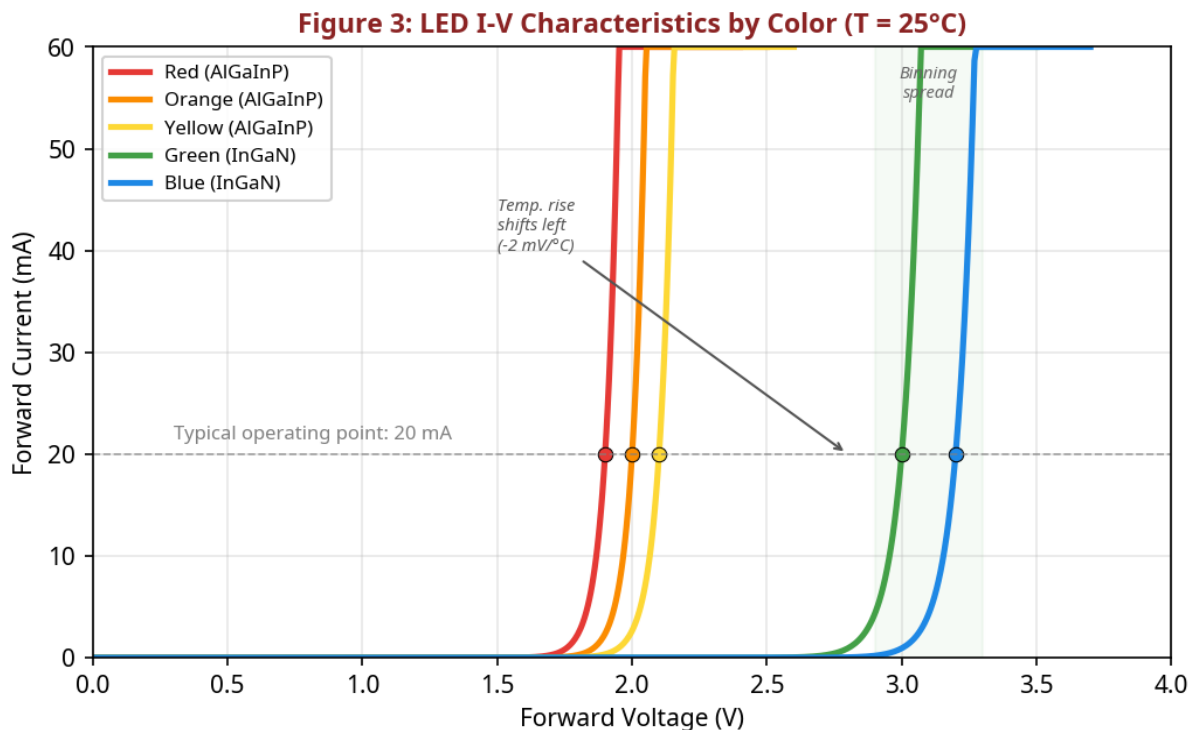


Figure 3: Measured I-V characteristics for five LED colors at 25°C. The exponential knee region shows why small voltage changes cause large current changes—and why constant-current regulation is essential for stable operation.

8. Best Practices and Design Checklist

The following checklist summarizes the key design decisions for reliable LED driving:

1. Determine maximum V_f for your LED color at the lowest operating temperature (V_f is highest when cold)
2. Calculate total string voltage: $V_{\text{string}} = N \times V_{f,\text{max}}$
3. Add minimum headroom: $V_{\text{supply,min}} = V_{\text{string}} + V_{\text{dropout}}$ (0.5–2 V for active drivers)
4. Verify supply exceeds $V_{\text{supply,min}}$ under worst-case load and line conditions
5. Choose driver type: Linear (lowest noise) or PWM (highest efficiency) based on application
6. Specify maximum current with thermal derating: I_{max} at T_{max}
7. Verify driver output voltage range covers V_{string} variation over temperature
8. Include thermal management: heat sink, [thermistor monitoring](#), or [active TEC cooling](#)
9. Add system monitoring: use LIO output for current feedback, LPGD for fault detection
10. Prototype with [ATI evaluation boards](#) before committing to production layout

Quick-Reference Card: LED Forward Voltage at a Glance**Red/Orange/Yellow (AlGaInP):** $V_f = 1.8\text{--}2.4\text{ V}$, $\text{TCV} = -2\text{ mV/}^\circ\text{C}$ **Green/Blue/White (InGaN):** $V_f = 2.9\text{--}3.5\text{ V}$, $\text{TCV} = -3\text{ mV/}^\circ\text{C}$ **Headroom rule:** $V_{\text{supply}} > N \times V_{f,\text{max}} + V_{\text{driver,dropout}}$ **Thermal rule:** Derate current 2.5% per 10°C above 25°C **Noise rule:** For <1% optical ripple, use ATI linear drivers (noise < 6 μA P-P)**Protection:** Always use OTP + OCP for LEDs costing > \$1 or in safety-critical systems**Frequently Asked Questions (FAQ)****Q: What is the forward voltage of a red LED?**

A typical red LED (AlGaInP material) has a forward voltage of 1.8–2.2 V at 20 mA and 25°C . The exact value depends on the specific wavelength, manufacturer binning, and operating current.

Q: Why do blue and green LEDs have higher forward voltage than red?

Blue and green LEDs use InGaN semiconductors with wider bandgaps (2.7–3.4 eV) compared to AlGaInP used in red LEDs (1.8–2.2 eV). Higher bandgap energy requires more voltage to inject carriers across the junction.

Q: How does temperature affect LED forward voltage?

LED forward voltage decreases with rising temperature at approximately $-2\text{ mV/}^\circ\text{C}$ for AlGaInP (red/yellow) and $-3\text{ mV/}^\circ\text{C}$ for InGaN (green/blue/white). This can cause overcurrent in resistor-limited circuits.

Q: Can I use a laser driver to drive LEDs?

Yes. ATI laser drivers are designed for the even more demanding requirements of laser diodes. Their ultra-low noise, precise current control, and comprehensive protection features make them ideal for high-end LED applications.

Q: What is the minimum supply voltage for a series LED string?

$V_{\text{supply,min}} = N \times V_{f,\text{max}} + V_{\text{headroom}}$. For a 6-white-LED string: $6 \times 3.3\text{ V} + 2\text{ V} = 21.8\text{ V}$ minimum. Use a 24 V supply for adequate margin.

Q: Why is constant-current driving better than a resistor for LEDs?

A constant-current driver maintains exact LED current regardless of supply voltage variations, temperature changes, and LED aging. A resistor cannot compensate for these variables, leading to $\pm 20\%$ or more current variation.

Q: What noise level is acceptable for LED driving?

For general illumination, noise below 1% of DC current is acceptable. For precision optical measurements, noise below 0.01% is needed. ATI linear drivers achieve 300 nA P-P noise—orders of magnitude below most LED driver ICs.

Q: How do I calculate the ballast resistor for an LED?

$R = (V_{\text{supply}} - N \times V_f) / I_{\text{LED}}$. Example: $(12\text{ V} - 3 \times 3.0\text{ V}) / 0.020\text{ A} = 150\ \Omega$. Power rating: $P = I^2 \times R = 0.060\text{ W}$ (use > 0.125 W resistor).

Q: What causes LED thermal runaway?

Thermal runaway is a positive feedback loop: temperature rise reduces V_f , which increases current in resistor-limited circuits, which increases power dissipation, which further raises temperature. A constant-current driver breaks this loop.

Q: Which ATI driver is best for low-noise LED applications?

The ATLSXA116 offers the lowest noise at 300 nA P-P with 6.5–16 V input range. For lower voltage systems (3–5.5 V), the ATLSXA106 provides 1.5 μA P-P noise at up to 500 mA.

Q: How many LEDs can I connect in series?

$N_{\max} = (V_{\text{supply}} - V_{\text{headroom}}) / V_{f,\max}$. With a 24 V supply, 2 V headroom, and white LEDs (3.3 V max): $N = (24-2)/3.3 = 6$ LEDs maximum.

Q: What is LED binning and why does it matter?

Binning is the manufacturer's process of sorting LEDs by forward voltage, wavelength, and luminous intensity. Vf bins can span 0.5 V or more. Without binning awareness, series strings may have unequal current sharing.

Q: Do ATI laser drivers have evaluation boards?

Yes. Most ATI laser driver families (ATLSXA103, ATLSXA104, ATLSXA201, ATLSXA212, etc.) have evaluation boards available for rapid prototyping. Visit the [ATI laser driver page](#) for availability.

Q: What protection features do ATI drivers provide?

ATI laser drivers include over-temperature protection (OTP), over-current protection (OCP), under-voltage protection (UVP), soft-start, and loop-good indication (LPGD). Some models also provide real-time current monitoring (LIO).

Q: How do I select between linear and PWM ATI drivers?

Choose linear drivers (ATLSXA103/104/106/116/117) for lowest noise and fastest modulation. Choose PWM drivers (ATLSXA201/202/212/216/217) for highest efficiency and highest current. See the [selection guide](#) for details.

References and Related ATI Resources

Internal ATI Resources:

- [ATI Laser Driver Product Family](#) – Complete product lineup with specifications and pricing
- [ATI Product Catalog](#) – Full range of analog and mixed-signal products
- [ATI White Papers Library](#) – Technical resources and application guidance
- [ATI NTC Thermistors](#) – Temperature sensing for LED thermal management
- [ATI TEC Modules](#) – Active cooling for high-power LED assemblies
- [ATI TEC Controllers](#) – Precision temperature control systems
- [Original LED Forward Voltage Article \(2014\)](#) – Earlier treatment of this topic
- [Contact ATI Engineering](#) – Application support and custom solutions

External References:

- Schubert, E.F., *Light-Emitting Diodes*, 3rd ed., Cambridge University Press, 2018.
- Sze, S.M. and Ng, K.K., *Physics of Semiconductor Devices*, 4th ed., Wiley, 2021.
- CIE Technical Report 127:2007, *Measurement of LEDs*.
- JEDEC Standard JESD51-51, *Implementation of the Electrical Test Method for Measurement of Real Thermal Resistance and Impedance of LEDs*.

Next Steps: Get Started with ATI Laser Drivers for Your LED Application

1. Browse the [ATI laser driver product page](#) for specifications and pricing.
2. Request an evaluation board to test with your specific LED configuration.
3. [Contact ATI engineering](#) for application-specific recommendations.
4. Visit www.analogtechnologies.com for the complete product portfolio.