For a light-emitting diode (LED) to generate light, the minimum voltage required is widely considered to be the emitter’s bandgap divided by the elementary charge. Here we show for many classes of LEDs, including those based on perovskite, organic, quantum-dot and III–V semiconductors, light emission can be observed at record-low voltages of 36–60% of their bandgaps, exhibiting a large apparent energy gain of 0.6–1.4 eV per photon. For 17 types of LEDs with different modes of charge injection and recombination (dark saturation currents of $10^{-39}–10^{-15}$ mA cm$^{-2}$), their emission intensity-voltage curves under low voltages show similar behaviours. These observations and their consistency with the diode simulations suggest the ultralow-voltage electroluminescence arises from a universal origin—the radiative recombination of non-thermal-equilibrium band-edge carriers whose populations are determined by the Fermi-Dirac function perturbed by a small external bias. These results indicate the potential of low-voltage LEDs for communications, computational and energy applications.
The development of LEDs\textsuperscript{1–6} has created far-reaching impacts on lighting, display and information industries. Emerging LED technologies, including organic LEDs (OLEDs)\textsuperscript{4–8}, quantum-dot LEDs (QLEDs)\textsuperscript{9–11}, and perovskite LEDs (PeLEDs)\textsuperscript{2–18}, are gaining significant attention due to their promise as next-generation light sources. The key mechanisms responsible for the light emission from LEDs are electroluminescence (EL), the radiative recombination of injected electrons and holes under an external voltage. It has been suggested that the minimum (threshold) driving voltage required to create photons from the EL process equals to the bandgap ($E_g$) of the emissive material divided by the elementary charge ($q$), in consideration of the energy conservation principle\textsuperscript{19,20}, while free energy considerations allow a marginal energy gain of a few $kT$ (where $k$ is the Boltzmann constant and $T$ is the temperature)\textsuperscript{21}. Studies suggested that the minimum voltage may be reduced through various mechanisms, including thermally assisted upconversion\textsuperscript{22–26}, sequential charge injection\textsuperscript{27}, interfacial dipoles\textsuperscript{28}, triplet-triplet annihilation upconversion (TTA–UC)\textsuperscript{29,30}, and Auger processes\textsuperscript{10,31–34}. Recently, an operating voltage as low as 77% of the nominal bandgaps was observed for LEDs based on III–V semiconductors, and this was attributed to enhanced radiative recombination enabled by a novel quantum well design\textsuperscript{35}. For OLEDs, a minimum operating voltage of ~0.5$E_g$/q was reported\textsuperscript{30,31,33}, though whether a TTA process could be used to explain the origin of this low operating voltage is still a subject of debate\textsuperscript{30,33,36}. Sub-bandgap operating voltages were also observed for perovskite\textsuperscript{11} and quantum-dot OLEDs\textsuperscript{10,11,26,27,32,37,38} (Supplementary Table 1). These observations lead to an open question of what the lowest possible driving voltages really are for electroluminescence, and whether they stem from the same origins. Ultralow-voltage operation of LEDs may create new opportunities for next-generation energy-efficient optoelectronics.

In this work, using high-sensitivity photon counting measurements on 17 types of LEDs, we show that EL at voltages significantly below the emitter’s bandgap is possible for many classes of LEDs, and is not exclusive to a few novel material systems. The similar shapes of the EL-voltage curves reveal a universal origin of ultralow-voltage operation, in spite of the very different modes of charge injection and recombination in these devices.

**Results**

We began our investigation by measuring the minimum operating voltages of LEDs based on emerging material systems. Perovskite LEDs were our first experimental subjects. We fabricated iodine-based near-infrared “FPI”\textsuperscript{14,39}, “NFPI”\textsuperscript{40} and bromide-based green-emitting “PCB”\textsuperscript{41} perovskite LEDs with peak EQEs of ~10% (Fig. 1a–c and Supplementary Fig. 1a–c. See Methods for fabrication details). We observed that, for these perovskite LEDs, the minimum voltages for EL were 1.3 V, 1.3 V and 1.9 V (Fig. 1a to c), while the EL peak photon energies were 1.55 eV, 1.56 eV and 2.4 eV (Supplementary Fig. 2a, b and Supplementary Fig. 3b), respectively (the minimum detectable photon flux is ~10$^{-6}$ photons·s$^{-1}$ m$^{-2}$ for our standard measurement setup, see Methods for details). Here, EL peak photon energies are used to provide conservative estimates of the bandgaps. The minimum operating voltages observed were 83%, 83% and 79% of the bandgaps for FPI, NFPI and PCB PeLEDs, respectively. The observation of near- or sub-bandgap operating voltages for these LEDs is consistent with recent findings for efficient PeLEDs\textsuperscript{12,13,39,42,43}. We performed similar experiments for phosphorescent OLEDs based on tris(2-phenylpyridine)iridium (III) (Ir(ppy)$_3$) and bis[2-(4,6-difluorophenyl)pyridinato-C2,N](picolinate)iridium (Flrpic)\textsuperscript{44}, thermally activated delayed fluorescence (TADF) OLEDs based on 1,2,3,5-tetrakis(carbazol-9-yl)-4,6-dicyanobenzene (4CzIPN)$^2$, polymer OLEDs based on poly(9,9-diocetylfluorene-alt-benzothiadiazole) (F8BT)$^45$, fluorescent small-molecule OLEDs based on rubrene\textsuperscript{41}, and II–VI chalcogenide QLEDs based on CdSe/ZnS quantum dots\textsuperscript{46}. Sub-bandgap voltage EL was similarly observed (Fig. 1d to h).

Further, we measured commercial III–V LEDs based on GaN, AlGaP, GaP, GaAsP, InAlGaP, AlGaAs, GaAs, and InGaAsP. Sub-bandgap voltage operation was similarly observed. For GaAsP-based LEDs with an $E_g$ of 1.95 eV (Fig. 1i), EL could be clearly observed under an applied voltage of 1.45 V (0.74$E_g$) using the same measurement setup (See Methods for details). Importantly, the EL spectra remained unshifted as the driving voltages varied from above to clearly below the bandgaps (Fig. 2 and Supplementary Figs. 2, 3), while sub-bandgap voltage EL is shown to be a general phenomenon.

A key scientific question is what the minimum voltages really are for the operation of LEDs. To find an answer to this problem, we employed a highly sensitive photon detection system (Supplementary Fig. 4) for the determination of the onset of EL, greatly enhancing the measurement sensitivity. The weak photon emission (minimum detectable photon flux is ~10$^{-9}$ photons·s$^{-1}$ m$^{-2}$, which is 7 orders of magnitude more sensitive than the standard measurement setup; see Materials and Methods for details). EL was detected from our perovskite LEDs at voltages equivalent to 0.4–0.6 $E_g$ (Fig. 3a), representing the lowest driving voltages reported for perovskite LEDs to date. For FPI, NFPI and PCPB PeLEDs emitting at ~800 nm, ~790 nm and ~515 nm, the minimum voltages for observing EL were ~0.86 V, ~0.72 V and ~1.52 V, corresponding to $qV_m/E_g$ of ~55%, ~46% and ~63% respectively (Fig. 3a). Here, $V_m$ denotes the measured minimum voltage required for generating detectable EL. The apparent energy gap $\Delta E = E_g - qV_m$ was as large as 0.9 eV. This is more than an order of magnitude greater than the room-temperature thermal energy ($kT = 26$ meV at 300 K). Using bandpass filters with cut-off wavelengths close to the materials’ bandgaps (Supplementary Fig. 5), we confirmed that these photons did not arise from the recombination of sub-bandgap states.

We similarly observed minimum operating voltages of 1.75 V (0.73$E_g$/q) and 1.9 V (0.72$E_g$/q) for phosphorescent OLEDs based on Ir(ppy)$_3$ and Flrpic, 1.8 V (0.77$E_g$/q) for TADF OLEDs based on 4CzIPN, 0.8 V (0.36$E_g$/q) for fluorescent small-molecule OLEDs based on rubrene, 1.6 V (0.74$E_g$/q) for polymer OLEDs based on F8BT, 1.1 V (0.56$E_g$/q) for II–VI QLEDs based on CdSe/ZnS QDs, and 1.7 V (0.63$E_g$/q), 1.4 V (0.65$E_g$/q), 1.3 V (0.62$E_g$/q), 1.25 V (0.62$E_g$/q), 0.78 V (0.56$E_g$/q), 0.72 V (0.48$E_g$/q), 0.60 V (0.43$E_g$/q) and 0.54 V (0.42$E_g$/q) for inorganic LEDs based on GaN, AlGaP, GaP, GaAsP, InAlGaP, AlGaAs, GaAs and InGaAsP, respectively (Fig. 3b to d). Record-low operating voltages were found for each class of LEDs (Fig. 3e). We noted that the apparent energy gaps ($\Delta E$) were on the order of ~1 eV. A summary of measured minimum voltages and $\Delta E$ values we observed is provided in Table 1, and the measurements were reproducible across a number of devices (Supplementary Fig. 6). Our experiments collectively demonstrate that the EL operation at sub-bandgap voltages is a universal phenomenon across different classes of LEDs, and the operating voltages can reach values of ~0.5$E_g$/q or below. For NFPI perovskite devices, rubrene devices and commercial inorganic NIR devices, the measured $V_m$ values were even below the threshold voltage limits set by the TTA/Auger processes (Fig. 3f). These cannot be explained by previously published mechanisms\textsuperscript{25–27,29,31–34}. The lower EQE values at low voltages (Supplementary Fig. 7) arise from the larger fraction of non-radiative recombination losses typically observed in semiconductors under low injection conditions\textsuperscript{35}. Our measurements in Fig. 3e show that there is still a large number of photons being emitted under ultralow voltages, suggesting that...
Fig. 1 EL intensity-voltage characteristics of different classes of LEDs. a Near-IR-emitting FAPbI₃ (FP1) perovskite LED. b Near-IR-emitting NFPI perovskite LED. c Green PCPB perovskite LED. d Phosphorescent OLED based on Ir(ppy)₃. e TADF OLED based on 4CzIPN. f Polymer OLED based on F8BT. g Fluorescent small-molecule OLED based on rubrene. h II-VI QLED based on CdSe/ZnS QDs. i Commercial III–V inorganic LED based on GaAsP. The bandgaps for each emissive material are marked by dashed lines. Insets are schematics of the respective LED device structures.

The relation between the EL intensity and the applied voltage can be described by Eq. (3) (See Supplementary Note 2 for details).

$$\log(I_{EL}) = \frac{\log(eq)}{nKT} V + \log(EQE) - \log(eW \left( \frac{qR_{i}\lambda}{nKT} e^{\frac{q}{nKT}} \right)) \quad \text{(3)}$$

in which $W$ is the Lambert W-function. EQE can be determined experimentally from the current–voltage and EL intensity-voltage data. The EL intensity-voltage characteristics of our LEDs could be nicely fitted by this preliminary model (Supplementary Fig. 8).

We note that the dark saturation current density ($j_0$) varies greatly across different classes of LEDs, from $\sim 10^{-39}$ mA cm$^{-2}$ for Flrpic, $\sim 10^{-35}$ mA cm$^{-2}$ for PCPB perovskite, $\sim 10^{-27}$ mA cm$^{-2}$ for F8BT, $\sim 10^{-25}$ mA cm$^{-2}$ for CdSe/ZnS to $\sim 10^{-15}$ mA cm$^{-2}$ for InGaAsP devices (Fig. 3g and Supplementary Table 2). $j_0$ contains important information on the physics of charge recombination in LEDs, and it depends on $E_g$ and $\Lambda$ (Supplementary Note 2). The measured $j_0$ exhibit a negative correlation with $E_g$. To allow a clearer comparison across different material systems, we also calculated the bandgap-weighted dark saturation current densities ($j_0e^{\frac{q}{nKT}}$) for the LEDs we measured (Fig. 3h). Interestingly, the ‘weighted’ $j_0$ values of the perovskite LEDs based on FPI, NFPI and PCPB now approaches the regime for III–V semiconductor LEDs.

The current–voltage curves of various classes of LEDs exhibit very different characteristics (Supplementary Fig. 8a). However, all LEDs show remarkably similar EL intensity voltage behaviours under low operating voltages (Fig. 3e), and follow the conventional diode equation described below as Eq. (1), where the light emission is the diode dark saturation current density ($j_0$) is negatively correlated with $E_g$ in a general form of $j_0 = A \exp(-E_g/kT)$, where $A$ is related to material properties. See Supplementary Note 1 for details), $n$ is the ideality factor, $k$ is the Boltzmann constant, $T$ is the temperature, and $V$ is the external voltage applied across the diode with minimum influence from series resistance ($R_s$) at low voltages. While Eq. (1) is generally derived for unipolar p–n junction diodes, we see here it clearly models the electron-hole recombination current for these diodes irrespective of the choice of semiconductor materials and charge-injection electrodes. In essence, the EL intensity ($I_{EL}$) is linked to the current density via the external quantum efficiency (EQE) of the LED (Eq. (2)).

$$j = j_0 \left[ e^{\frac{q(V-jR_s)}{nKT}} - 1 \right] \quad \text{(1)}$$

$$I_{EL} = \text{EQE}\frac{j}{q} \quad \text{(2)}$$
The charge transport and recombination processes are in and OLEDs tested are slightly higher, likely due to the reason that based on FPI. The ideality factors for most of the PeLEDs, QLEDs below the bandgap voltage.

Negative correlation between

holes) dominates over the other, injection where one type of charge carriers (either electrons or complementary Fig. 9). In a related case of imbalanced charge the same photon

applied voltage, reducing the apparent threshold voltage for the case the same LEDS based on the same or similar emissive materials, in which

threshold voltages are generally higher for wider-bandgap LEDs.

To gain further insight, we employ a widely used device simulation software "Sentaurus" to model the emission behaviour of LEDs. We constructed model devices including a leadiodide perovskite LED, and a standard phosphorescent OLED based on Ir(ppy)3 (Fig. 4) (See Methods and Supplementary Tables 3, 4 for details). The simulation results (Fig. 4c, d) show that both types of LEDs are capable of generating EL at voltages well below the bandgaps in a fashion similar to what we have observed with our experimental setup (Fig. 3), consistent with the LED model we described. From the simulations, it can be seen that the intensities of the output photon fluxes correlate strongly with the densities of injected charges. At operating voltages significantly below the bandgap, there are appreciable levels of electron and hole populations contributing to the radiative recombination (Fig. 4e, f). These results are consistent with the conventional diode law and with our proposed mechanism for sub-bandgap EL. At similar photon fluxes, the modelled Ir(ppy)3 OLED operates at higher voltages in comparison to that of the perovskite LED. This could be attributed to the generally lower densities of states in organic semiconductors leading to smaller carrier concentrations in OLEDs.

Using Eq. (3) it is possible to further understand how the emissive material properties and the device design influence the apparent threshold voltages for EL (Fig. 5). An interesting observation is that higher driving voltages are required to generate the same photon flux for emissive materials with larger $E_g$ (Fig. 5a). Indeed, this offers an explanation for why the apparent threshold voltages are generally higher for wider-bandgap LEDs. Similarly, higher series resistance tends to increase the apparent

\[ \text{EL intensity} \sim \text{Density of states} \times \text{Injection efficiency} \]

models originally developed for conventional inorganic semiconductors can also be used to describe the general behaviour of emerging classes of LEDs with vastly different material properties, pointing toward a universality in the operating principles of different LEDs.

![EL spectra of perovskite LEDs under above- and sub-bandgap voltages](image-url)

**Fig. 2 EL spectra of perovskite LEDs under above- and sub-bandgap voltages.** a, b EL spectra of a FPI perovskite LED driven at different bias above and below the bandgap voltage. c, d EL spectra of a NFPI perovskite LED driven at different bias above and below the bandgap voltage. e, f EL spectra of a PCPB perovskite LED driven at different bias above and below the bandgap voltage.
Perovskite LED
FAPbI₃ (FPI)
Perovskite LED
PCPB perovskite
Perovskite LED
NFPI perovskite
Phosphorescent OLED
Ir(ppy)₃
Flrpic
4CzIPN
Rubrene
Fluorescent small-molecule OLED
CdSe/ZnS

Organic LED
FiRpic
4CzIPN
rubrene and F8BT.

Fig. 3 EL intensity-voltage characteristics at near- and sub-bandgap voltages for different LEDs. a Perovskite LEDs based on FPI, NFPI and PCPB. b Organic LEDs based on Ir(ppy)₃, Flrpic, 4CzIPN, rubrene and F8BT. c II-VI QLED based on CdSe/ZnS QDs. d III-V inorganic LEDs based on InGaAsP, GaAs, AlGaAs, InAlGaP, GaAsP, GaP, AlGaP and GaN. e Collection of EL intensity-voltage curves for different classes of LEDs in the same panel. f Measured qVm/Eg of different classes of LEDs. The shaded area denotes the region where the measured qVm/Eg falls below the limits set by TTA or Auger processes. g Dark saturation current densities (j0) of different classes of LEDs. h j0exp(Eg/kT) of different classes of LEDs. i Vm versus j0 for different classes of LEDs. Vm is the measured minimum voltage for detectable EL.

Table 1 Measured minimum operating voltages of different LEDs studied in this work.

| Device type          | Emissive material | EL peak wavelength (nm) | Bandgap (Eg) (eV) | Measured minimum voltage (Vm) (V) | ΔE (eV) | qVm/Eg |
|----------------------|-------------------|-------------------------|-------------------|-----------------------------------|---------|--------|
| Perovskite LED       | FAPbI₃ (FPI)      | 800                     | 1.55              | 0.86                              | 0.69    | 55%    |
| Perovskite LED       | NFPI perovskite   | 790                     | 1.56              | 0.72                              | 0.84    | 46%    |
| Perovskite LED       | PCPB perovskite   | 515                     | 2.40              | 1.5                               | 0.9     | 63%    |
| Phosphorescent OLED  | Ir(ppy)₃         | 521                     | 2.38              | 1.7                               | 0.68    | 71%    |
| Phosphorescent OLED  | Flrpic            | 473                     | 2.63              | 1.9                               | 0.73    | 72%    |
| TADF OLED            | 4CzIPN            | 528                     | 2.35              | 1.72                              | 0.63    | 73%    |
| Polymer OLED         | F8BT              | 538                     | 2.30              | 1.7                               | 0.6     | 74%    |
| Fluorescent small-   | Rubrene           | 563                     | 2.20              | 0.8                               | 1.4     | 36%    |
| molecule OLED        |                   |                         |                   |                                   |         |        |
| II-VI QLED           | CdSe/ZnS          | 631                     | 1.96              | 1.1                               | 0.86    | 56%    |
| III-V inorganic LED  | GaN               | 461                     | 2.69              | 1.7                               | 1.00    | 63%    |
| III-V inorganic LED  | GaAsP             | 570                     | 2.17              | 1.25                              | 0.92    | 60%    |
| III-V inorganic LED  | GaP               | 593                     | 2.09              | 1.3                               | 0.79    | 62%    |
| III-V inorganic LED  | AlGaP             | 633                     | 1.95              | 1.4                               | 0.55    | 65%    |
| III-V inorganic LED  | InAlGaP           | 800                     | 1.55              | 0.78                              | 0.77    | 50%    |
| III-V inorganic LED  | AlGaAs            | 820                     | 1.51              | 0.72                              | 0.79    | 48%    |
| III-V inorganic LED  | GaAs              | 880                     | 1.40              | 0.60                              | 0.8     | 43%    |
| III-V inorganic LED  | InGaAsP           | 960                     | 1.29              | 0.54                              | 0.75    | 42%    |
threshold voltages especially under larger bias, when the fractional potential drop on the active material becomes smaller. Low-voltage operation is improved with higher EQE and with reduced series resistance (Fig. 5b, c). Using perovskite LEDs as examples, both FPI and PCPB devices showed lower apparent threshold voltages with higher EQEs (Supplementary Fig. 11a, b). In principle, series resistance consists of both bulk resistance (related to the resistivity and thickness of the layers) and contact resistance (which includes the influence of charge-injection barriers). The effects of series resistance were tested in NFPI perovskite LEDs by reducing the thickness of the hole-transport layers (HTLs), poly(N,N′-bis-4-butylphenyl-N,N′-bisphenyl)benzidine (poly-TPD). The apparent threshold voltages can be lowered from 2.4 V to 1.4 V (Supplementary Fig. 11c). Similarly, for the PCPB perovskite LEDs, by replacing the electron-transport layers (ETLs) with (1,3,5-triazine-2,4,6-triyl)tris(benzene-3,1-diyli)tris(diphenylphospine oxide) (PO-T2T, \( \mu_e \sim 4.4 \times 10^{-3} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \)), an electron-transport material with much higher electron mobility than commonly used electron-transport materials such as bathophenanthroline (Bphen, \( \mu_e \sim 5.2 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \)) and 1,3,5-tris(1-phenyl-1H-benzimidazol-2-yl)benzene (TPBi, \( \mu_e \sim 3.3 \times 10^{-5} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \)), the apparent threshold voltages could be markedly reduced from 2.8 V to 1.9 V (Supplementary Fig. 11d).

As discussed, raising the barrier height to charge injection may contribute to the series resistance of LEDs through contact resistance, potentially raising the operating voltages for the same output photon fluxes. To exemplify this effect, FPI perovskite LEDs with different HTLs (Supplementary Fig. 11e) were tested. The apparent threshold voltages are generally higher for LEDs based on HTLs with higher hole-injection barriers (Supplementary Fig. 11f). To further clarify the issue of charge injection, using Setfos we constructed a perovskite LED model with a variable charge-injection barrier at the hole-transport layer/anode barrier, which has been shown to improve the device performance by reducing the series resistance.
interface (Supplementary Fig. 12). As the barrier to hole injection increases, significant reductions of photon fluxes are observed for higher driving voltages (Supplementary Fig. 12b). The reduction in photon flux is directly related with the reduced hole densities for devices with higher hole-injection barriers (Supplementary Fig. 12c). The effect of charge-injection barrier becomes less pronounced in the low-voltage regime. These effects are consistent with the LED model (Eqs. (1)–(3)) considering charge-injection barriers as contributors to the series resistance.

We discuss below the origin of the ultralow-voltage EL phenomenon, consistent with the close relation between EL and the diode law on which the aforementioned analyses are based. Under zero bias, thermal distribution of band-edge carriers is in balance with carrier recombination (leading to $j_0$). At this point, EL does not occur as the net external current is zero due to the balance between the drift current (caused by built-in fields from band bending or interfacial dipoles) and the diffusion current (from the gradient of carrier populations) (exemplified using a generic heterojunction diode, see Supplementary Fig. 13). When a small non-zero forward bias is applied, net external current arises from the reduced drift current due to weakened built-in fields. While the band-edge carrier population due to ambient temperature remains the same, carrier recombination including radiative and non-radiative processes increases due to the injection of external charges. The radiative component of carrier recombination gives rise to EL (Supplementary Fig. 14). It is important to note that EL at sub-bandgap voltages does not violate the energy conservation principle, as the energy for photon emission is readily supplied by the recombination of charge carriers near the band edges whose distribution is governed by the Fermi-Dirac function perturbed by a small bias (Supplementary Fig. 14b). This can be supported by our temperature-dependent measurements using an NFPI perovskite LED as an example. The EL intensity-temperature characteristics agree satisfactorily with the Fermi-Dirac distribution model (Supplementary Fig. 15). Device simulations using Setfos yield similar results (Supplementary Fig. 16). Compared with previously proposed mechanisms mostly for particular classes of LEDs$^{22,29,31–34}$, the present explanation is more fundamental and is applicable to a broad range of LEDs. It also explains ultralow-voltage EL (with $V_m$ near or less than $0.5E_g/q$) that cannot be addressed by former studies.

A useful outcome of the low-voltage operation of LEDs is that these devices may be more versatile than conventional expectations. To provide an example of how this may show benefits in practical applications, we employed our NFPI perovskite LEDs in a simple optical transmitter setup (Fig. 6). With the application of sub-bandgap driving voltage of 1 V ($0.65E_g/q$), we were able to generate 1/0 (on/off) signals with a signal-to-noise ratio of 20 dB (Fig. 6b). This result is in clear contrast to former studies, where optical signal transmission based on PeLEDs$^{33}$ and CMOS-integrated LEDs$^{34}$ used bias voltages of 2.5–3 V ($\sim 2E_g/q$). The corresponding energy consumption for our LEDs to produce an optical pulse is as low as 140 pJ per bit for input frequencies ranging from 100 Hz to 1 MHz. The output pulse width is ~15 ns for an input pulse width of ~18 ns under the frequency range tested (Fig. 6b, c and Supplementary Table 5). Further reductions in energy consumption and pulse width may be possible by using a pulse generator with a smaller minimum pulse width. Remarkably, the voltage needed for optical data transmission (1 V) is lower than the silicon bandgap (1.12 eV) divided by the elementary charge. As commonly used silicon integrated circuits (1 V) is lower than the silicon bandgap (1.12 eV) divided by the elementary charge. As commonly used silicon integrated circuits use 1 V chip supply voltage$^{35–37}$, LEDs operating at 1 V can be directly integrated into these circuits using the same voltage supply without the need for additional circuit elements, offering the possibility of delivering information wirelessly in optical coupling systems free from the influence of electromagnetic interference. Since it is theoretically possible to generate photons at voltages approaching zero, our results offer prospects for integrating these LEDs with low-voltage circuits for efficient optoelectronic operations, showing great potential in logic and communications applications$^{58,59}$.

**Discussion**

In summary, we have demonstrated, through high-sensitivity photon detection experiments, that the voltage for EL operation could reach values below 50% of the semiconductor bandgaps, exhibiting a large apparent energy gain of 0.6–1.4 eV per emitted photon.
The device structure of NFPI PeLEDs was ITO (135 nm)/PE-coated ZnO (20 nm)/NFPI (20 nm)/Poly-TPD (35 nm)/MoO3 (10 nm)/Ag (100 nm). Solutions of ZnO nanocrystals were spin-coated onto the ITO-coated glass substrate at 5000 rpm for 30 s and annealed at 100 °C for 10 min. The substrates were transferred into a N2 glovebox. Next, PE solution was spin-coated onto the ZnO surface at a speed of 5000 rpm for 60 s. The perovskite films were prepared by spin-coating the precursor solution onto the PE-coated ZnO films at 5000 rpm for 60 s, followed by annealing at 100 °C for 10 min. Poly-TPD (35 nm) was spin-coated at 4000 rpm for 60 s. Finally, the MoO3/Ag electrodes were deposited using a thermal evaporation system through a shadow mask under a base pressure of 4 × 10−4 Pa. The device area was 5.25 mm2 as defined by the overlapping area of the ITO films and top electrodes. All the devices were encapsulated with UV epoxy (NOA81, Thorlabs) before subsequent measurements.

Fabrication of PCPB perovskite LEDs. The perovskite precursor solution (molar ratio 5:5:2) was prepared by dissolving 110 mg lead bromide (PbBr2), 64 mg caesium bromide (CsBr), and 24 mg 2-phenylethylammonium bromide (PEABr) in 1 mL dimethylsulfoxide (DMSO) and stirring overnight at room temperature. The molecular additive used was 1,4,7,10,13,16-hexaoxacyclooctadecane (crowns) [2]. A Teflon-coated shadow mask with a pattern of 5 mm2 was prepared by evaporation of PEI on the ITO substrate and then coated with a crown molecule (PEIE). The substrates were then transferred into a N2 glovebox. Next, PE solution was spin-coated onto the ZnO surface at a speed of 5000 rpm for 60 s. The perovskite films were prepared by spin-coating the precursor solution onto the PE-coated ZnO films at 5000 rpm for 60 s, followed by annealing at 100 °C for 10 min. Poly-TPD (35 nm) was spin-coated at 4000 rpm for 60 s. Finally, the MoO3/Ag electrodes were deposited using a thermal evaporation system through a shadow mask under a base pressure of 4 × 10−4 Pa. The device area was 5.25 mm2 as defined by the overlapping area of the ITO films and top electrodes. All the devices were encapsulated with UV epoxy (NOA81, Thorlabs) before subsequent measurements.

Fabrication of rubrene OLEDs. The device structure of rubrene-based OLEDs was ITO (185 nm)/PEDOT:PSS (30 nm)/roll-coated rubrene (35 nm)/CaO (25 nm)/BnP (6 nm)/Al (120 nm). Organic materials were used as purchased without further purification. The devices were fabricated by thermal evaporation of a thin layer of rubrene on a substrate, followed by annealing at 100 °C for 10 min. Further deposition was done at room temperature. A 6-nm thin layer of BnP was deposited prior to the deposition of the top electrode. Devices were completed by evaporation of a 120-nm-thin layer of Ag. Metal deposition was achieved through a shadow mask. The device area was 5.25 mm2 as defined by the overlapping area of the ITO films and top electrodes. All the devices were encapsulated with UV epoxy (NOA81, Thorlabs) before subsequent measurements.
Fabrication of polymer OLEDs based on F8BT. The device structure of F8BT-based polymer OLEDs was ITO (185 nm)/PEDOT:PSS (40 nm)/TFB (25 nm)/QD (25 nm)/ZnO (65 nm)/Ag (120 nm). The PEDOT:PSS layer was deposited by a two-step spin-coating process at 1000 rpm for 10 s and 4000 rpm for 50 s, followed by annealing at 150 °C for 20 min. The QD layer of 10 nm was deposited under a base pressure of ~4 x 10⁻¹⁴ Pa. The deposition of the PEDOT:PSS layer was spin-coated from solution (in chlorobenzene, 12 mg ml⁻¹) at 2000 rpm for 60 s and baked at 150 °C for 20 min. CdSe/ZnS QD solution (in octane, ~15 mg ml⁻¹) and ZnO nanocrystals (in ethanol, ~30 mg mL⁻¹) were sequentially spin-coated onto the substrates at 2000 rpm for 60 s. Next, Ag electrodes (120 nm) were deposited by a thermal evaporation system under a base pressure of ~4 x 10⁻¹⁴ Pa. The deposition of the LEDs was achieved through a shadow mask. The active area of each device was 5.25 mm² as defined by the overlapping area of the ITO films and top electrodes. The devices were encapsulated with UVP epoxy (NOA81, Thorlabs) before subsequent measurements.

Characterization of LED performance. Current density-voltage (J−V) characteristics were measured using a Keithley 2400 source-meter unit. The luminance and EQE data were obtained using an Everfine OLED-200 commercial LED performance analysis system. The EQE measurement setup was calibrated against a standard integrating sphere coupled with an Ocean Optics QE-Pro spectrometer, and with a silicon detector. The photon flux and EL spectra were measured simultaneously using a charge-coupled device centre coupled over the light-emitting pixel. The luminance (in cd m⁻²) and visibility (in W sr⁻¹ m⁻²) of the devices were calculated based on the angular distribution functions of the LED emission and the known spectral response of the charge-coupled device. This standard setup can measure EL reliably below a minimum photon flux of ~1.4 x 10⁵ s⁻¹ m⁻², which corresponds to a minimum detectable photon flux of ~10⁸ s⁻¹ m⁻² for the LED devices. Additional EL spectra of the devices driven under near- and sub-bandgap voltages were collected by a fibre-coupled focus lens and measured using a QE Pro spectrometer (Ocean Optics).

High-sensitivity photon detection experiments. The measurement setup for the high-sensitivity photon detection experiments is illustrated in Supplementary Fig. 4a. Photons emitted from different classes of LEDs under near- and sub-bandgap voltages were detected by a Si-based single-photon avalanche photodiode (APD). The APD converts the photons from the LEDs into photocurrent, which is amplified by an amplifier. The photocurrent forms sharp pulses through a pulse shaper. These pulses are transmitted effectively through a BNC wire with low signal distortion. The transfer function forms sharp pulses through a pulse shaper. These pulses are transmitted effectively through a BNC wire with low signal distortion. The transfer function forms sharp pulses through a pulse shaper. These pulses are transmitted effectively through a BNC wire with low signal distortion. The transfer function forms sharp pulses through a pulse shaper. These pulses are transmitted effectively through a BNC wire with low signal distortion. The transfer function forms sharp pulses through a pulse shaper. These pulses are transmitted effectively through a BNC wire with low signal distortion. The transfer function forms sharp pulses through a pulse shaper. These pulses are transmitted effectively through a BNC wire with low signal distortion. The transfer function forms sharp pulses through a pulse shaper. These pulses are transmitted effectively through a BNC wire with low signal distortion. The transfer function forms sharp pulses through a pulse shaper. These pulses are transmitted effectively through a BNC wire with low signal distortion. The transfer function forms sharp pulses through a pulse shaper. These pulses are transmitted effectively through a BNC wire with low signal distortion. The transfer function forms sharp pulses through a pulse shaper. These pulses are transmitted effectively through a BNC wire with low signal distortion.

APD counts = g(Photons counts × w)

where w is the attenuation factor set by the neutral density filter and the collection efficiency of the optics. It is possible to calculate the actual photon counts from the raw data collected from the APD, according to

Photon counts = 1/w × g⁻¹(APD counts)

where g⁻¹(x) is the inverse function of g(x).

LED device simulations. In addition to the LED modelling and EL intensity-voltage data fitting presented in this work, we carried out device simulations for a lead-iodide perovskite LED and a Ir(ppy) OLED using a LED simulation software “Seithor®”. The preset parameters for these devices are available from the database of the device simulation package, with detailed settings and modifications presented in Supplementary Tables 3 and 4.

Data availability

The main data supporting the findings of this study are available within the article and its Supplementary Information. Additional data are available from the corresponding author upon reasonable request.

Received: 11 February 2022; Accepted: 16 June 2022; Published online: 04 July 2022

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Acknowledgements
This work was supported by the National Key Research and Development Program of China (grant no. 2018YFB2200401) (D.D.), the National Natural Science Foundation of China (NSFC) (61975180, D.D.), 62005243 (B.Z.), 22103069 (R.L.), the Kun-Peng Programme of Zhejiang Province (D.D.), the National Science Foundation of Zhejiang Province (LR21F050003) (B.Z.), the Fundamental Research Funds for the Central Universities (2020QNA5002) (B.Z.), Zhejiang University Education Foundation Global Partnership Fund (D.D.), and the Engineering and Physical Sciences Research Council (EPSRC) (R.H.F.). The authors acknowledge the administrative support from Minhui Yu and Yunben Zhao.

Author contributions
D.D. conceived the project and planned the study. Y.L. and S.X. fabricated and characterized the LEDs. Y.L. performed the high-sensitivity EL experiments. D.L. established the diode model and derived relevant equations. D.L. and S.X. carried out data fitting and analysis. B.G., R.L., Z.R., C.Z. and B.Z. contributed to experiments and analyses. D.D., Y.L., S.X. and D.L. wrote the manuscript. R.H.F. provided suggestions for substantial revisions. All authors contributed to the work and commented on the paper.

Competing interests
D.D., Y.L., S.X., D.L., B.Z., and B.G. are inventors on CN patent application: 202110879765.7. The remaining authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41467-022-31478-y.

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