Supplementary Information

Characterization of n-doped branches in nanotree LEDs

Kristi Adham[a], Yue Zhao [a], Pyry Kivisaari [b], Magnus T. Borgström*[a]

[a] NanoLund and Division of Solid State Physics, Lund University, Lund 221 00, Sweden

[b] Engineered Nanosystems Group, Aalto University, Aalto, 00076, Finland

Table 1: Core growth parameters

	TMIn molar fraction	PH_3 molar fraction	TEGa molar fraction	DEZn molar fraction	TESn molar fraction	V/III ratio
p segment	2.97×10^{-5}	6.92×10^{-3}	5.97×10^{-5}	0.73×10^{-5}	-	77.4
i segment	2.67×10^{-5}			-	9.8×10^{-7}	80.1
n segment	2.53×10^{-5}			-	2.14×10^{-5}	81.5

Table 2: Branch growth parameters

	TMIn molar fraction	PH_3 molar fraction	TEGa molar fraction	H_2S molar fraction	Dopant/III ratio
Sample 1	2.67×10^{-5}	1.38×10^{-2}	3.73×10^{-5}	3.17×10^{-7}	4.95×10^{-3}
Sample 2				3.94×10^{-7}	6.16×10^{-3}
Sample 3				5.22×10^{-7}	8.14×10^{-3}
Sample 4				7.69×10^{-7}	12×10^{-3}
Sample 5				14.70×10^{-7}	23×10^{-3}

Table 3: Atomic composition of GaInP branches measured in EDX-STEM

	1	2	3	4	5	6
P	45.8	45.89	48.48	51.83	52.68	52.19
Ga	11.23	10.55	15.22	14.65	13.72	10.21
In	42.97	43.56	36.3	33.53	33.6	37.61

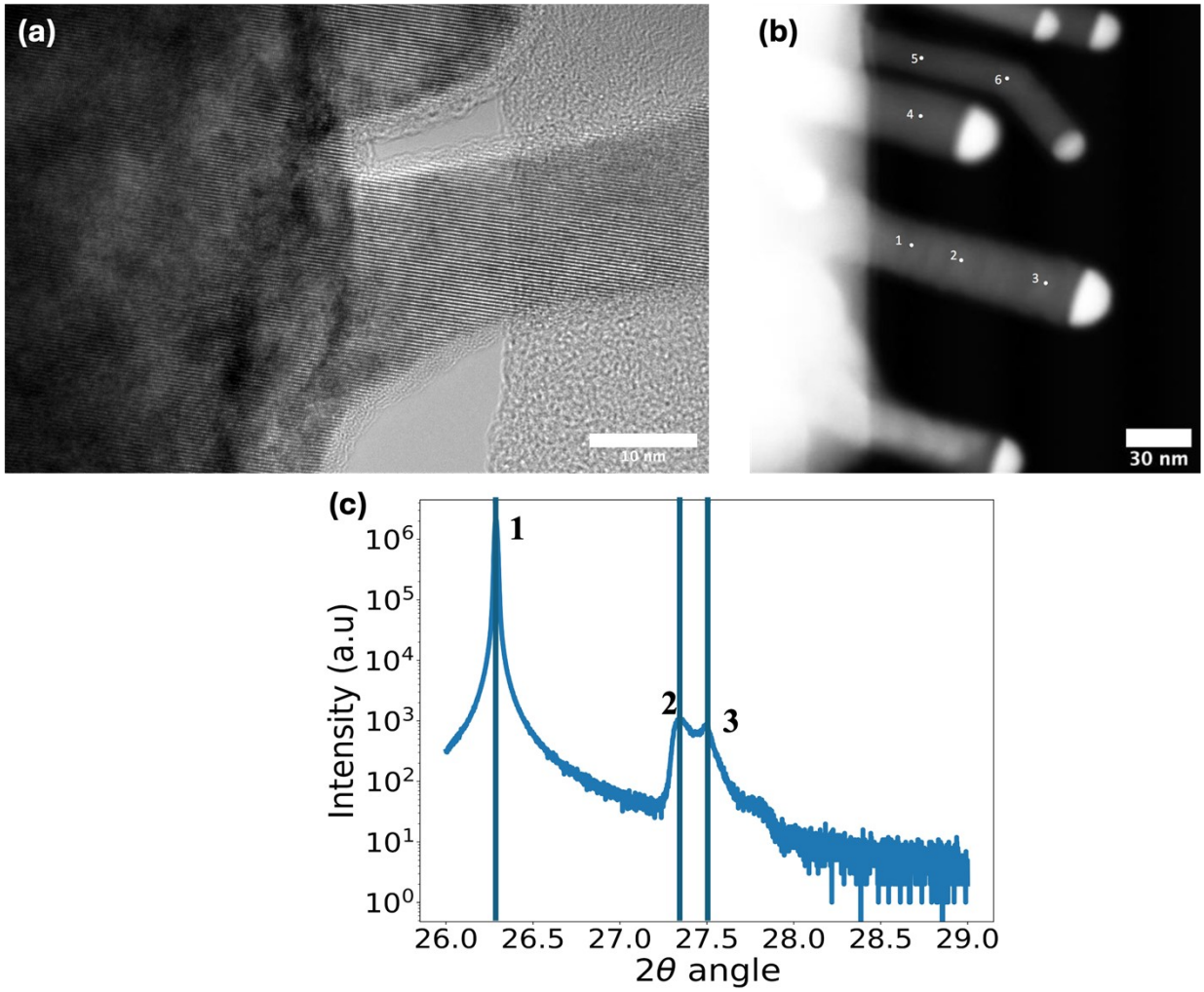

Figure S1: a) TEM image of the interface between a core and a branch where the propagation of lattice planes from the core to the branch is visible. b) Branches which have been analyzed in EDX. The numbered points represent the data point where the measurement has been performed. c) XRD results of as-grown core GaInP NW array. Peak 1 represents the InP substrate while peak 2 and 3 originate from the GaInP cores.

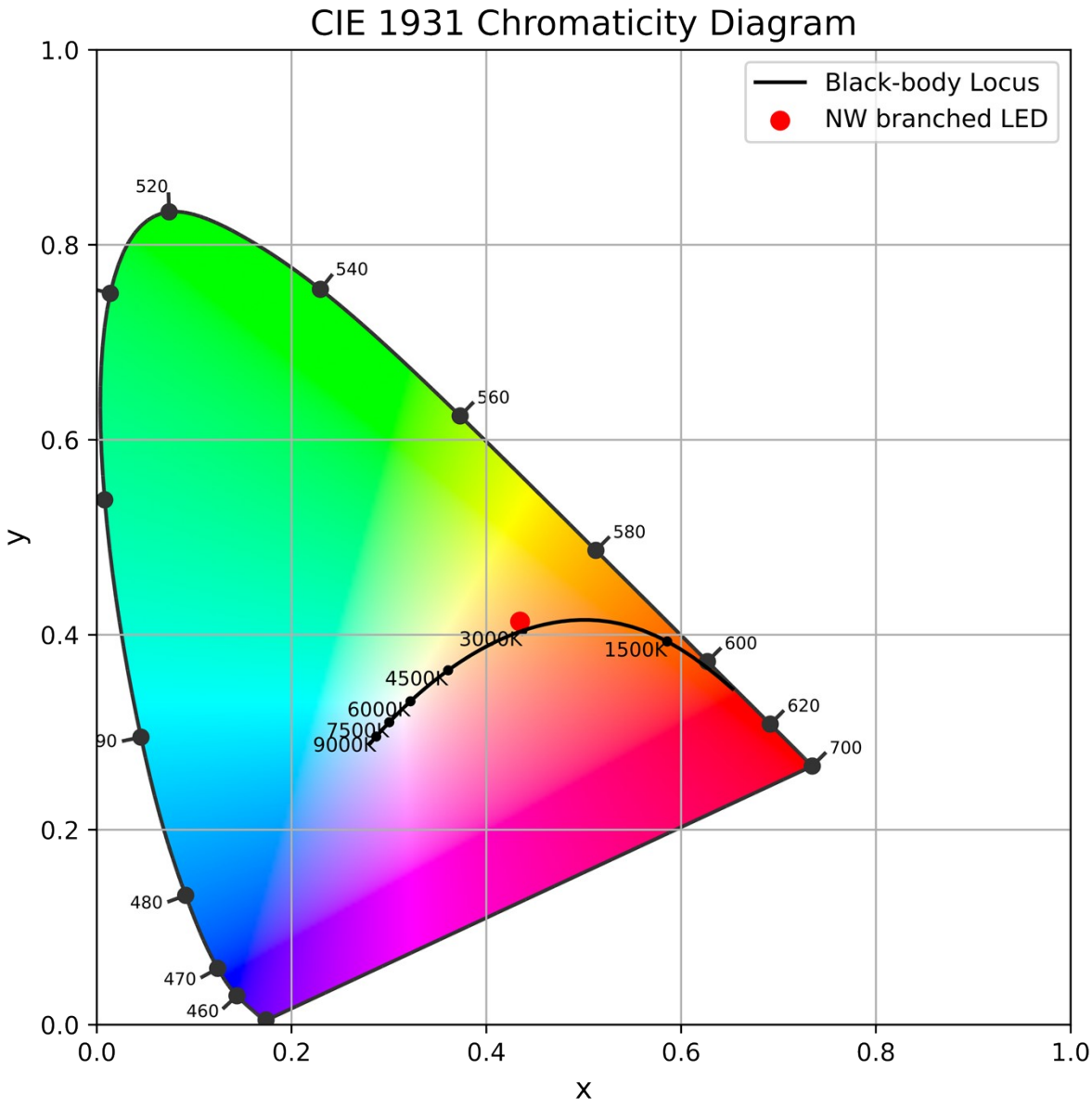

Figure S2: Chromaticity diagram of a nanotree LED sample, compared to the black-body locus. The CCT of the nanotree LED is approximately 3000 K.

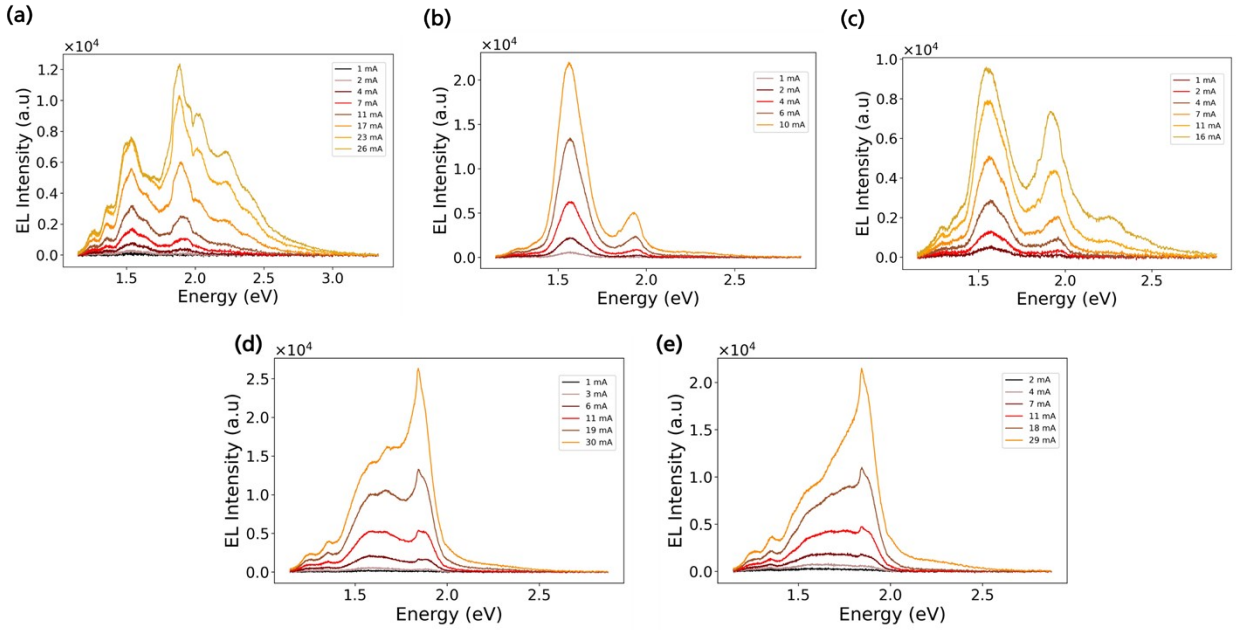

Figure S3: a)-e) EL spectrum of Samples 1-5, respectively, under different applied bias.

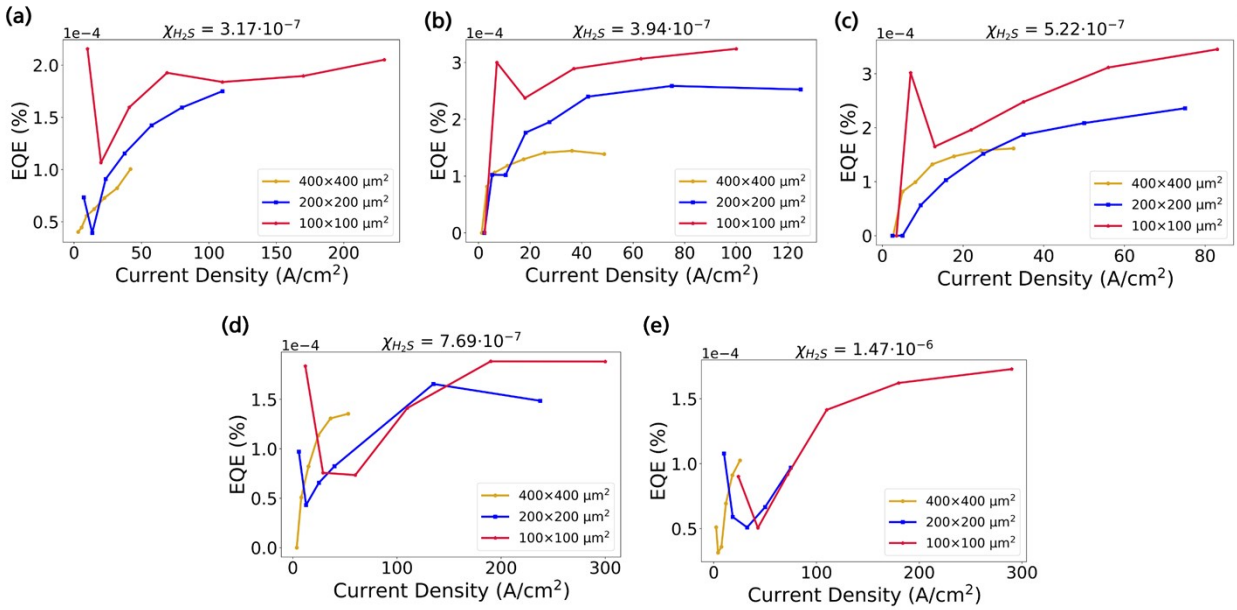

Figure S4: a)-e) EQE vs J of Samples 1-5, respectively, with varying active region area.

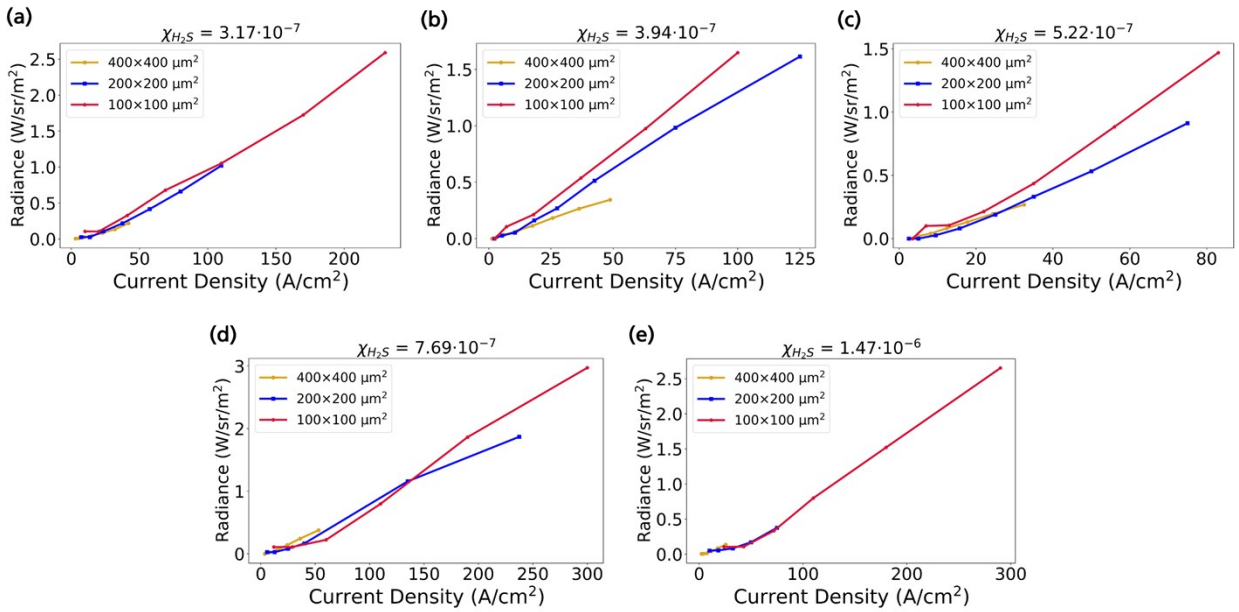

Figure S5: a)-e) Radiance vs J of Samples 1-5, respectively, with varying active region area.

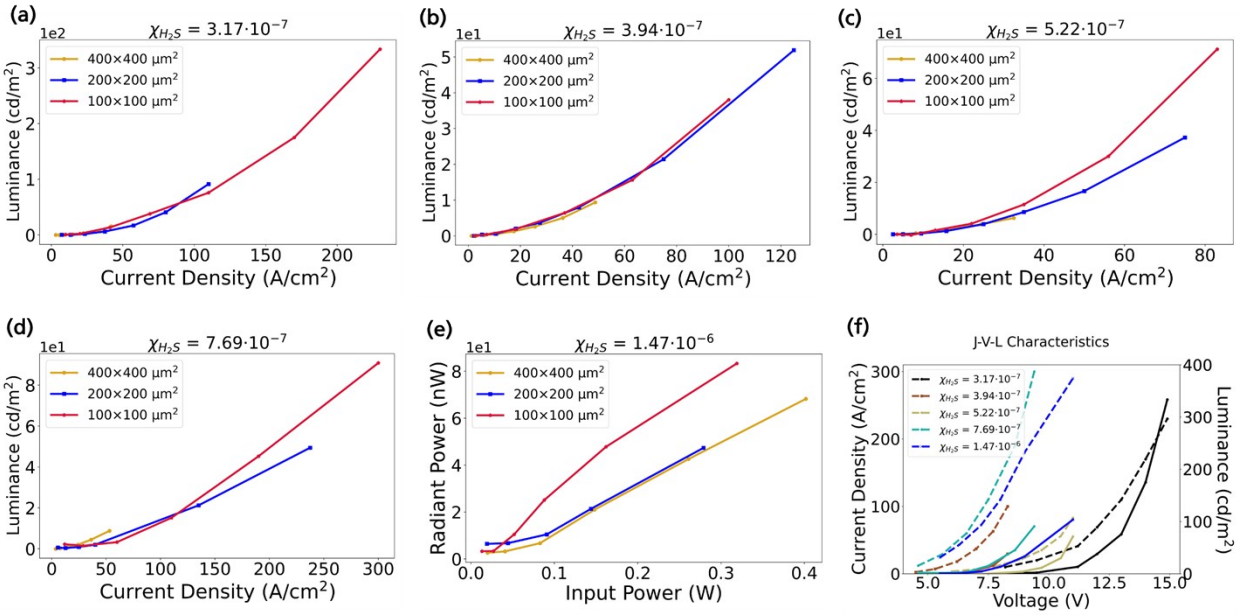

Figure S6: a)-e) Luminance vs J of Samples 1-5, respectively, with varying active region area. f) J-V-L characteristic of 100 × 100 µm² devices for different χ_{H2S}.

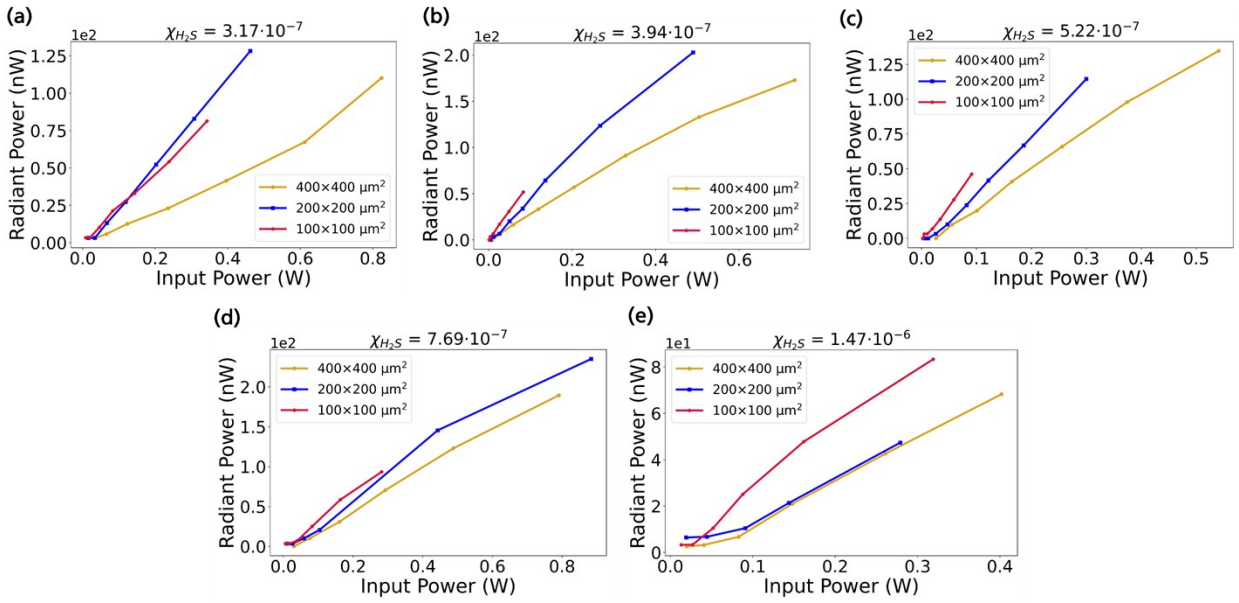

Figure S7: a)-e) Radiant Power vs Input Power of Samples 1-5, respectively, with varying active region area.

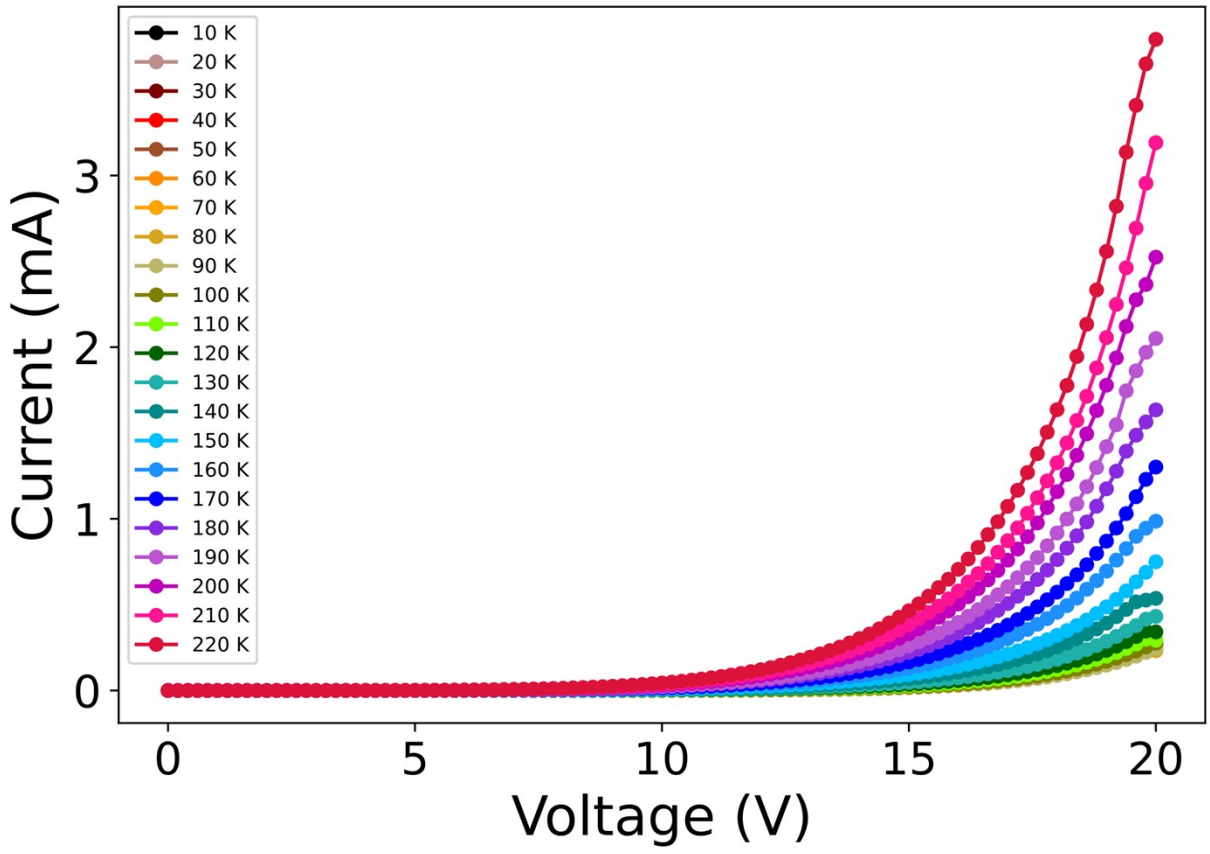

Figure S8: I – V relationship of a 200 × 200 μm² device from Sample 2 from 10 K to 220 K in steps of 10 K.

Simulation Details

The 3D drift-diffusion simulations were carried out in a 3 µm long nanotree sliced into half in the longitudinal direction by making use of symmetry. The simulation domain is illustrated in Figure S9, with the colormap representing the electrostatic potential at 1.8 V only for visualization purposes. The n-type region, intrinsic region, and p-type region of the trunk are each 1 µm long, and the branches are spread evenly over the intrinsic region. The number of branches in the domain is limited to 9 to reduce the computational cost, corresponding to a total of 18 branches in the respective complete nanotree. The width of the trunk is 200 nm (each side of the hexagon forming the trunk cross section is 100 nm). The width and length of the branches are 30 nm and 200 nm, respectively. The trunk consists of $Ga_{0.51}In_{0.49}P$, and the branches consist of $Ga_{0.25}In_{0.75}P$, with a corresponding band gap difference of 320 meV.
The simulations are based on the standard drift-diffusion model also deployed in e.g. Ref. [S1]. The contacts are described by the customary Dirichlet boundary conditions specifying the applied bias of the nanotree. Bulk Shockley-Read-Hall (SRH), radiative, and Auger recombination processes are included in the total recombination rate, and surface recombination velocity is implemented as a boundary condition following Ref. [S2]. The most important simulation parameters deployed here are listed as follows. The bulk SRH lifetimes for electrons and holes are $3.25 \cdot 10^{-8}$ s and $2.5 \cdot 10^{-6}$ s (respectively), the radiative recombination coefficient is $1.2 \cdot 10^{-10}$ cm^3s^{-1}, and the Auger coefficient is 10^{-30} cm^6s^{-1}. The electron and hole mobilities in the trunk are 2850 $cm^2V^{-1}s^{-1}$ and 175 $cm^2V^{-1}s^{-1}$, respectively. In the n- and p-type sections of the trunk, the ionized doping densities are always assumed to be 10^{18} cm^{-3}.

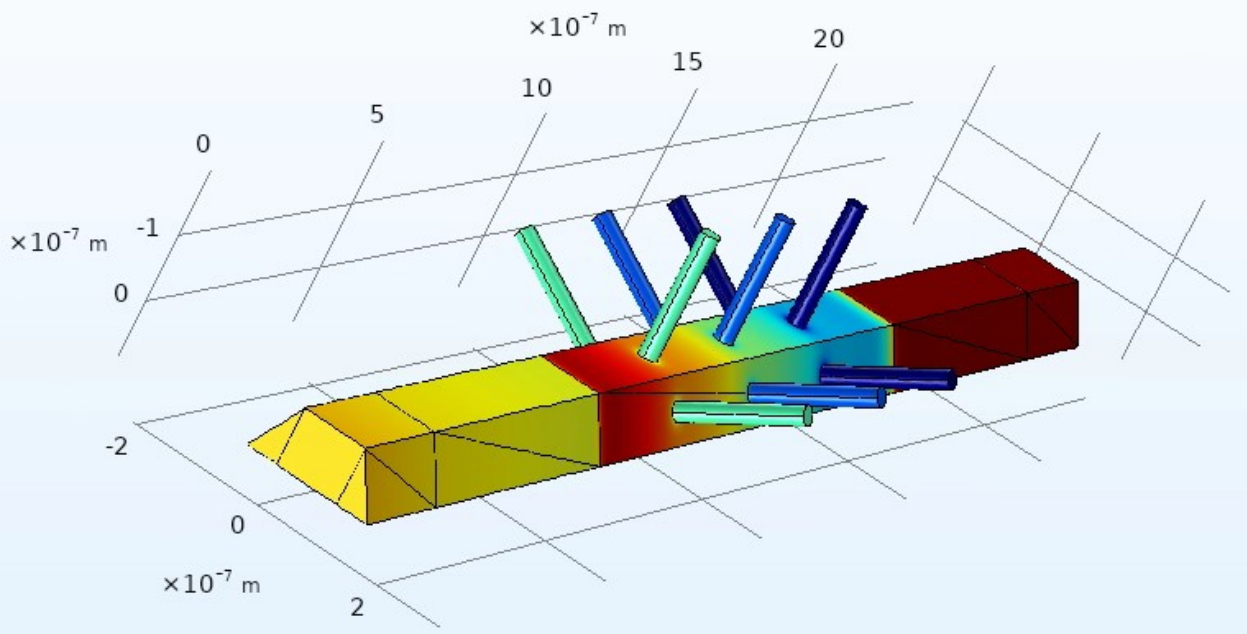

Figure S9: Simulation domain for the 3D drift-diffusion simulations. The colormap denotes the electrostatic potential at 1.8 V and is displayed here only for visulization purposes.

References

S1. P. Kivisaari, *Physical Review Applied*, 2020, **13**, 064035.
S2. R. B. Darling, *Physical Review B*, 1991, **43**, 4071.