A monolithic, back-gated diamond field-effect transistor for electrically tunable color centers

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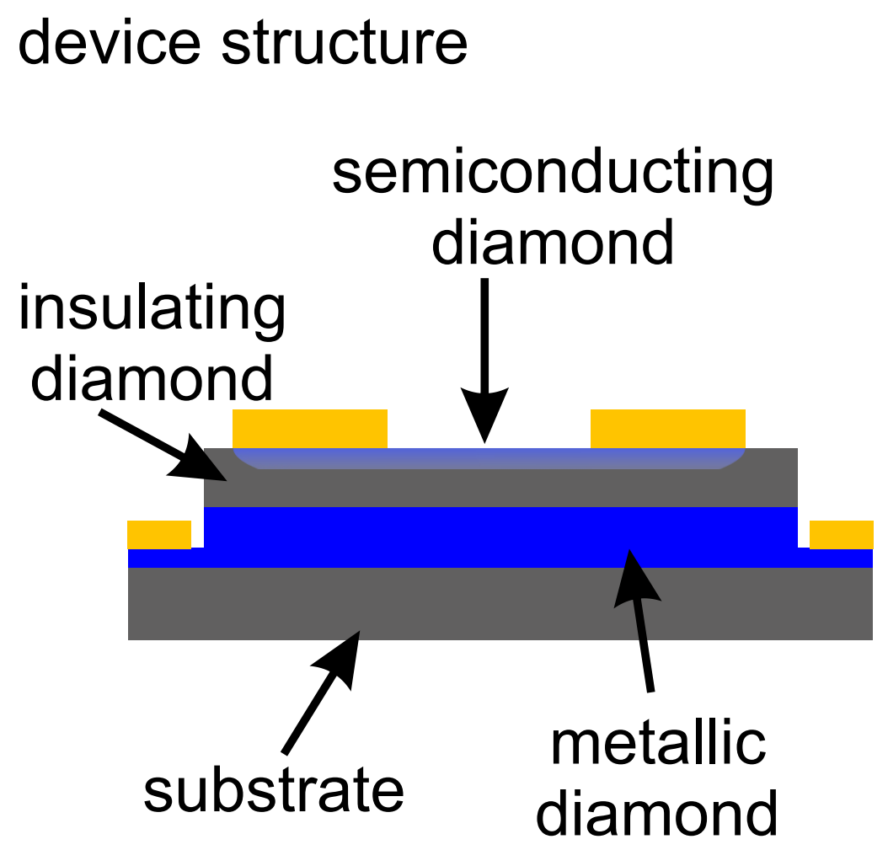
1 Motivation

- Diamond has outstanding properties as semiconductor
  - high frequency devices [1, 2]
  - high thermal conductivity
- Monolithic, diamond-based transistor can use these properties to get...
  - temperature independent 2DHG as tunable channel [3]
  - non-conductive diamond as dielectric [4]



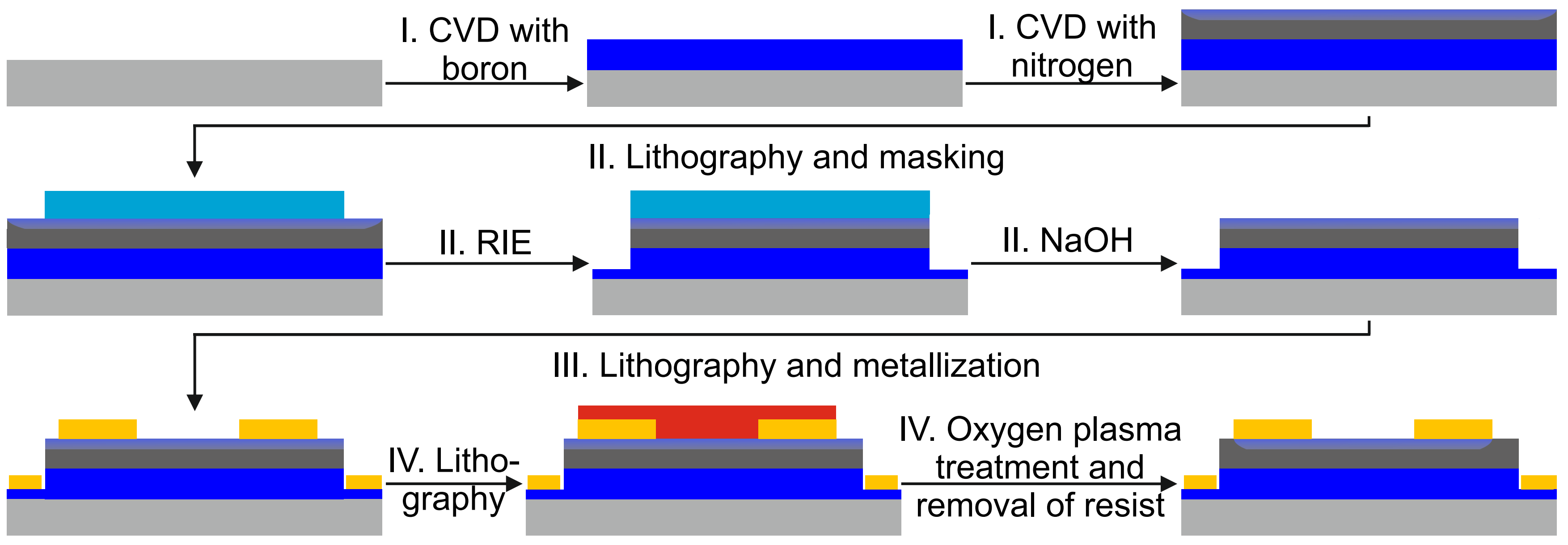
2 Sample preparations

I. CVD growth on (100)-oriented substrate diamond substrate
- sequential doping with boron (p-type) and nitrogen (n-type)

II. Structuring with reactive ion etching (Al as hard mask) is used to get contact to the back gate

III. Optical lithography to define electrical contacts

IV. Lithography to remove 2DHG in oxygen plasma (resist as mask)



3 Band structure

Layer sequence

- Degenerately boron-doped layer as metallic back gate
  - resistance <$10^{-2}\,\Omega$cm
- Lightly nitrogen-doped layer as dielectric layer
  - reduced doping concentration at the surface
- 2DHG on H-terminated surface as tunable channel

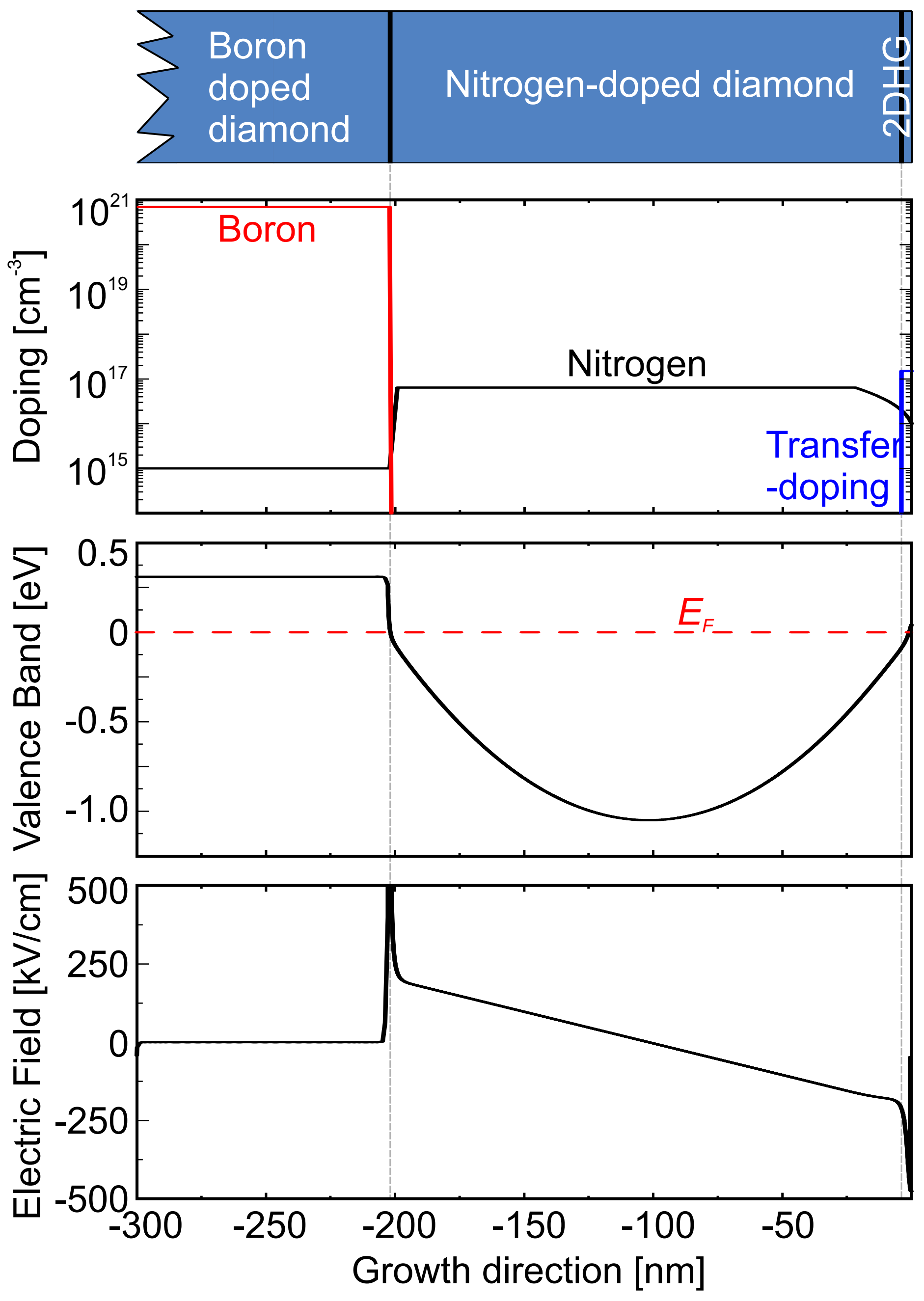
➡ Doping profile to calculate band structure

Band structure

- Band structure strongly depends on nitrogen concentration in dielectric layer
  - nitrogen-donors compensate holes in dielectric layer

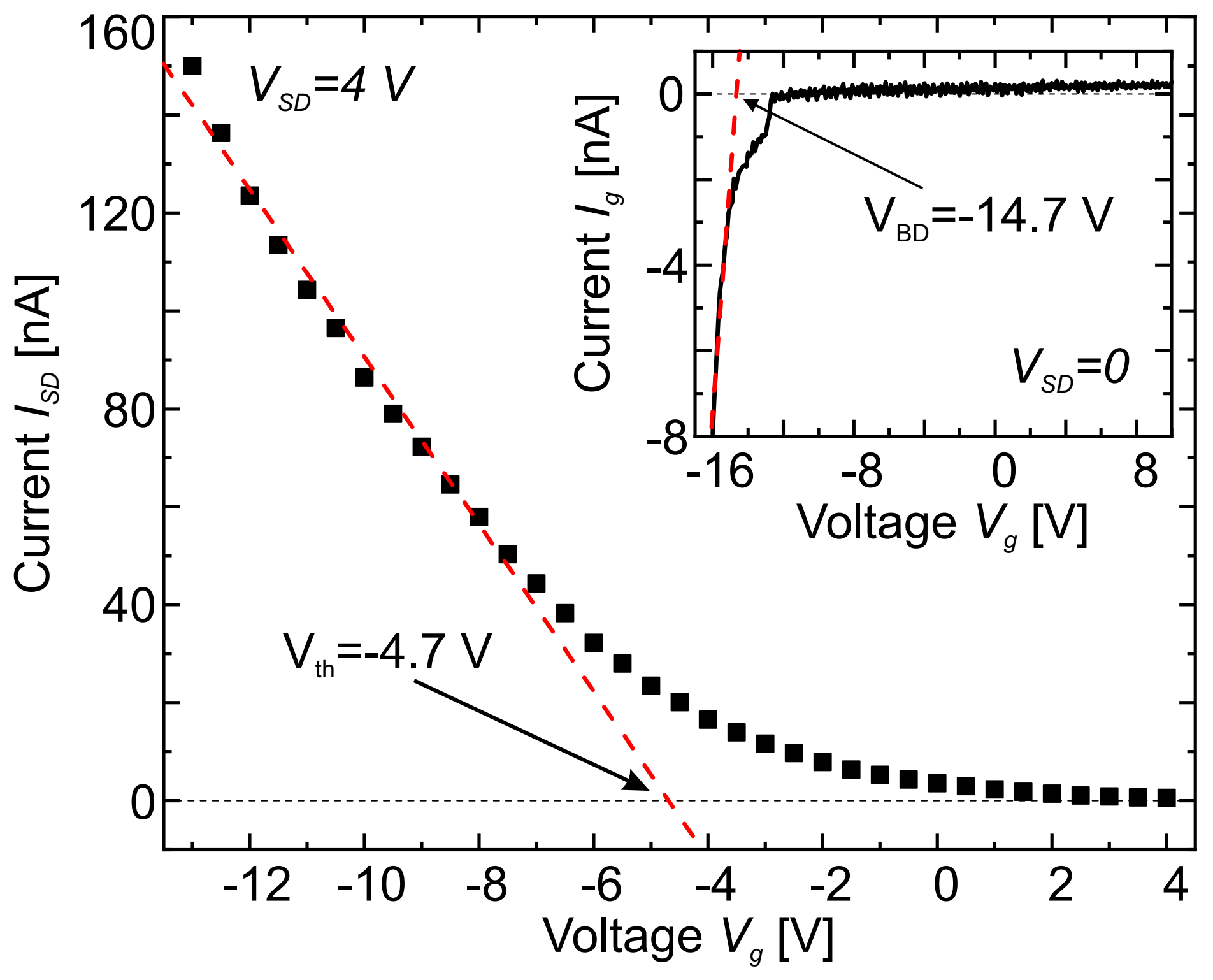
➡ Parabolic valence band

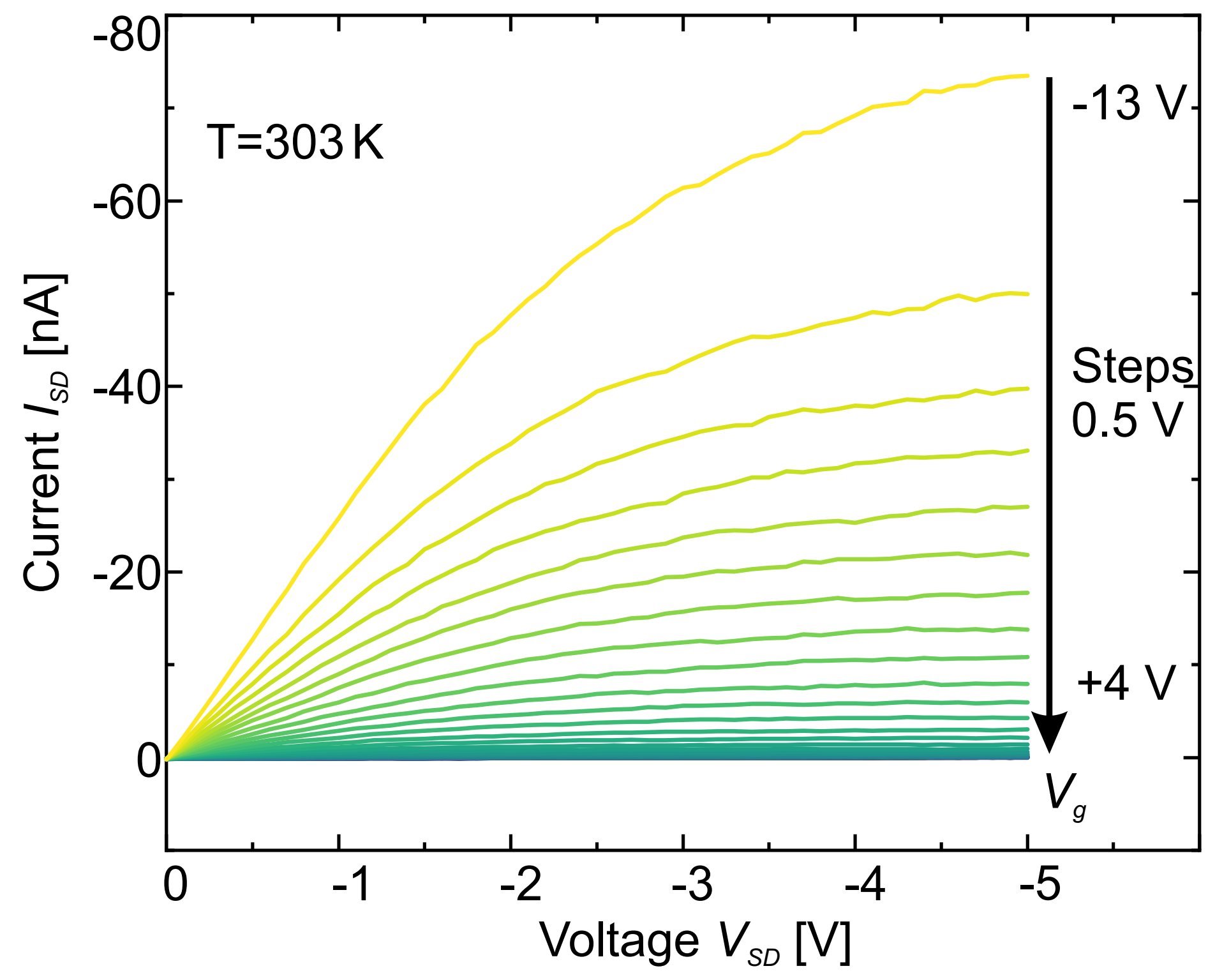
- High built-in electric field in the dielectric layer



4 Electrical characterization

- Capacitance of transistor is 9 pF at V_g=0
  - thickness of dielectric layer is 202 nm
- Source-Drain current-voltage characteristics
  - conductivity increases for negative gate voltages
- Transconductance
  - threshold voltage of V_{th}= -4.7 V
  - field-effect mobility of μ= 0.06 cm^2/Vs





- Source-Gate current-voltage characteristics
  - low leakage current (<1 nA) through dielectric

➡ Nitrogen-doped diamond suitable as dielectric

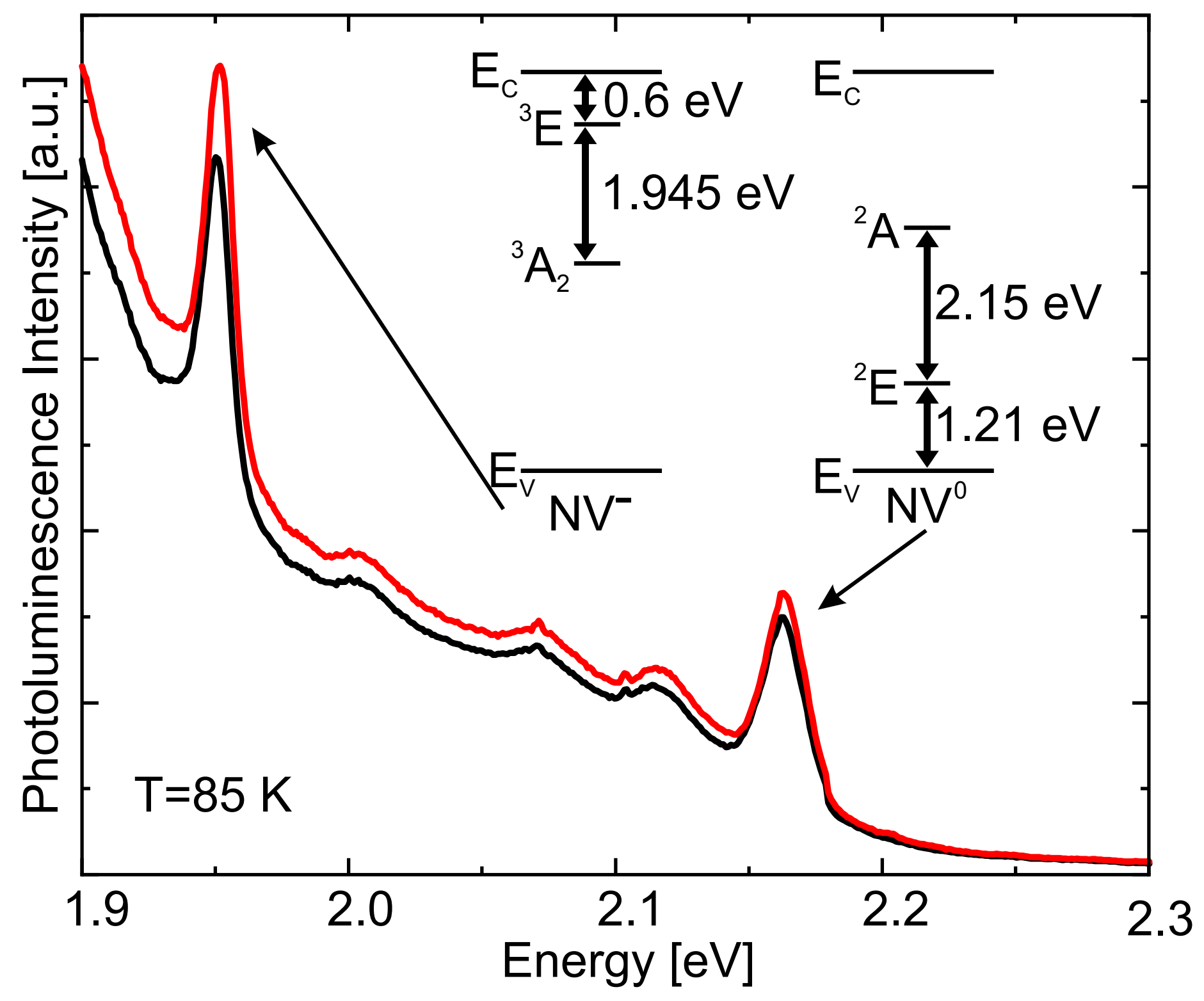
- breakdown voltage of V_{BD}= -14.7 V

➡ Breakdown field of E_{BD}= 725 kV/cm

➡ Tunable carrier density up to $2.4\cdot10^{12}$ cm^{-2}

➡ **Functional p-type enhancement-mode FET!**

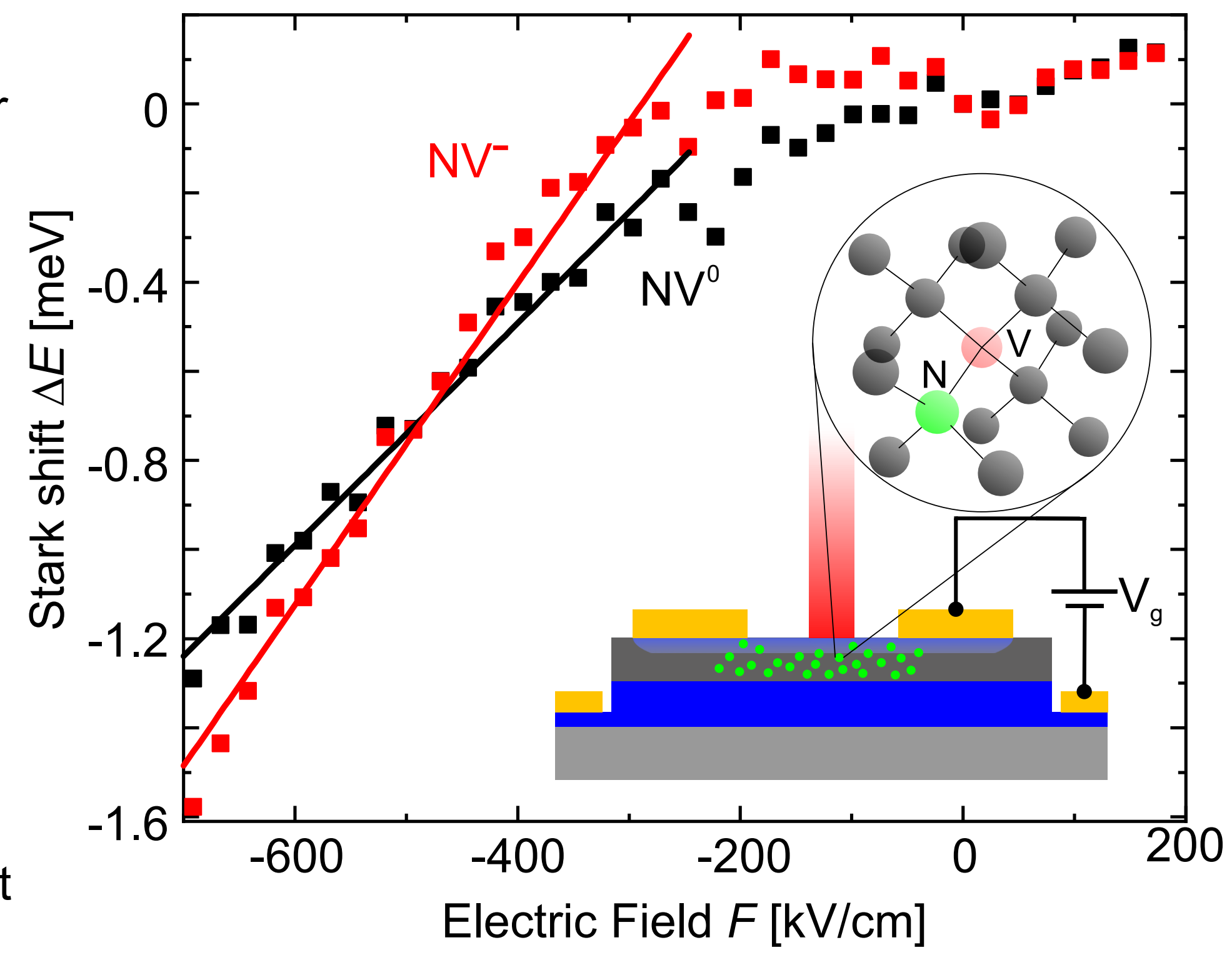
5 NV-centers, embedded in transistor structure

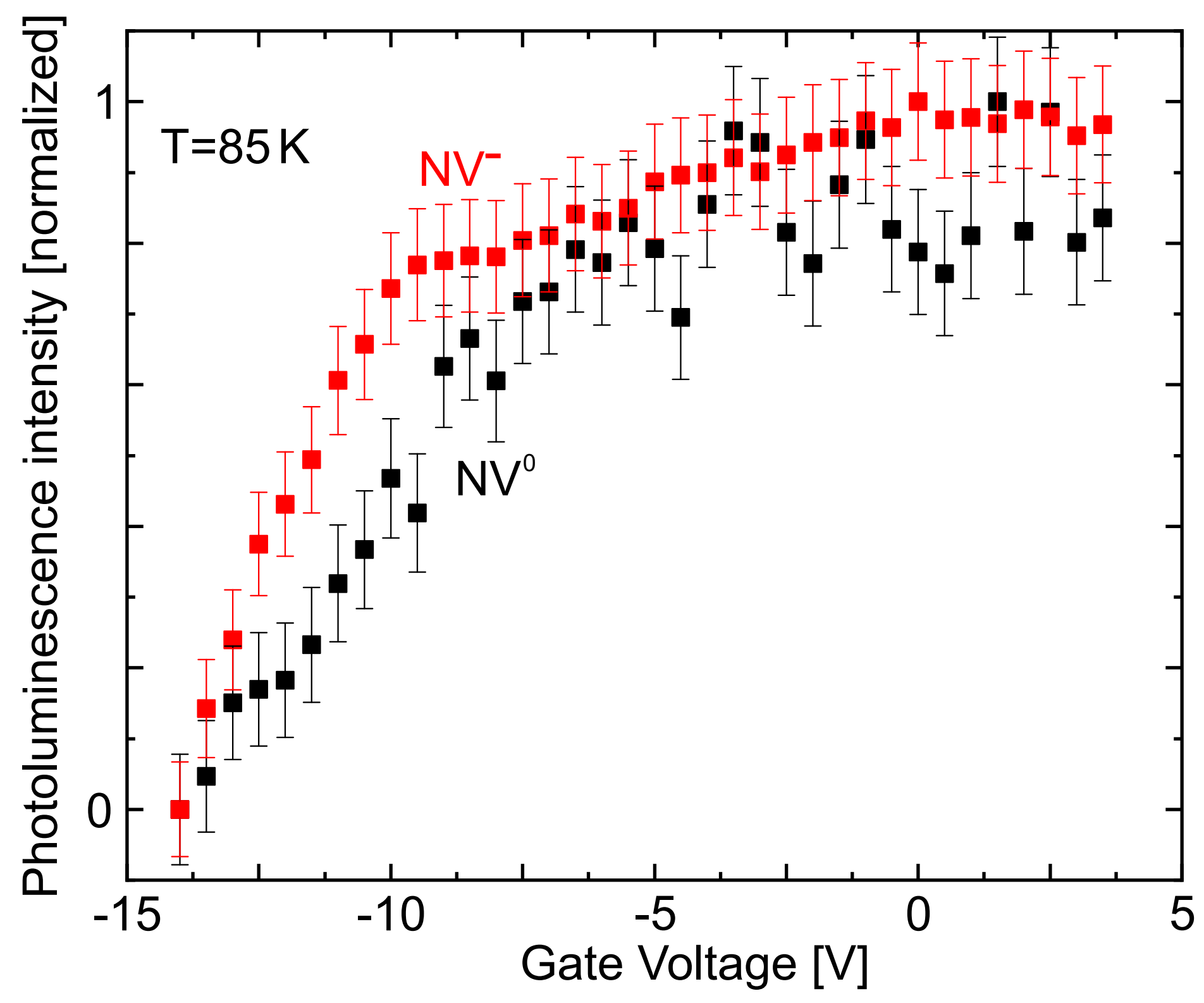


Stark Shift

- NV-centers expected to be in the dielectric layer
- Photoluminescence shows broad signals for both charge states of the NV-centers
  - possible reason for broadening is Stark shift due to built-in electric field of the device
- Determine Stark shift by applying an additional electric field, using the gate voltage
  - Stark shift is 2.5 μeV/kVcm^{-1} for NV^0 and 3.6 μeV/kVcm^{-1} for NV$^-$

➡ 17 % of observed FWHM is due to Stark shift



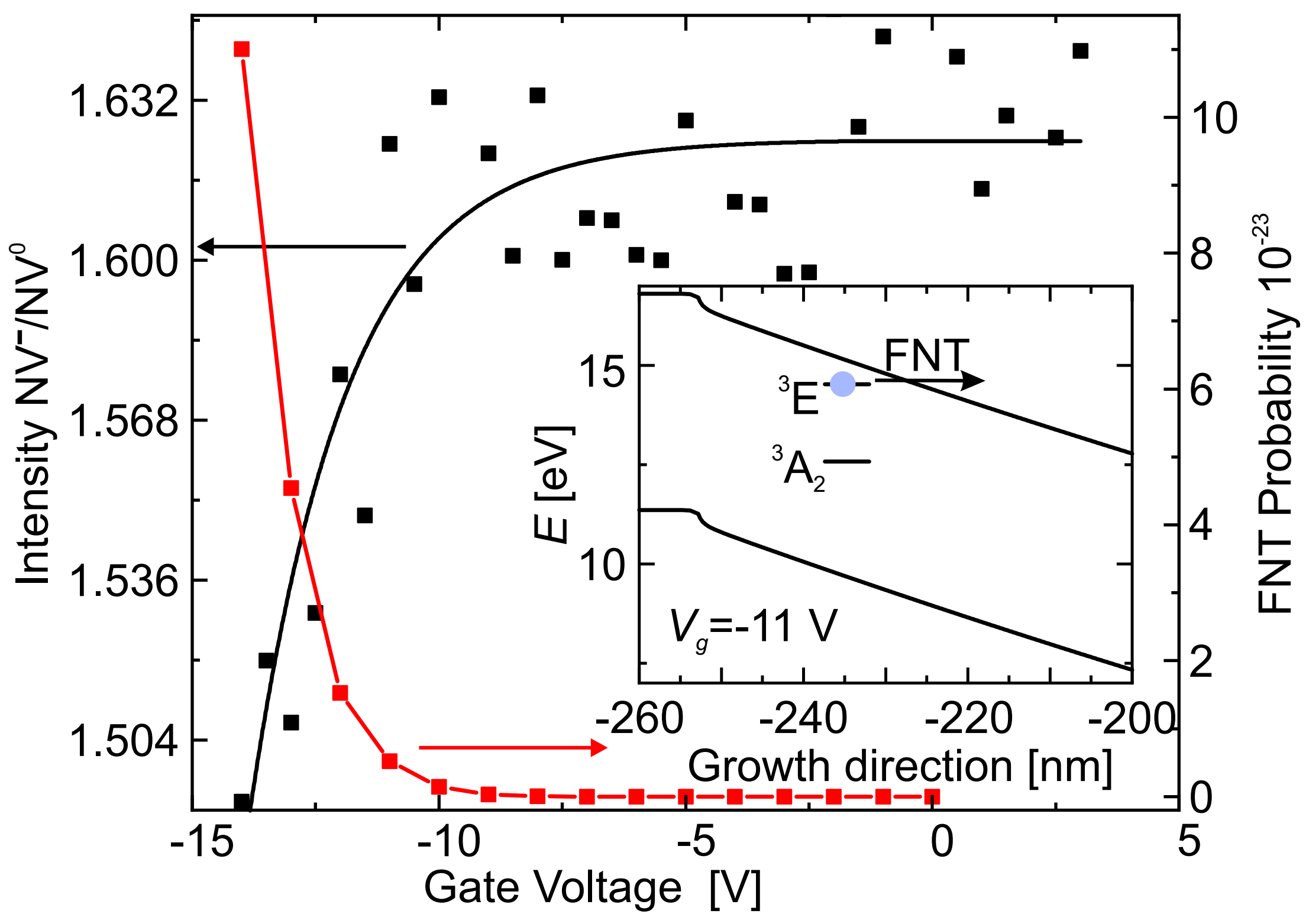


Charge state manipulation

- Intensity of NV-centers decreases for V_g< -9 V
- Explained by Fowler-Nordheim tunneling (FNT) process [5]

$$\mathrm{FNT} = \frac{e^2F^2}{16\pi^2\hbar V_0}\exp\left(-\frac{4}{3}\frac{\sqrt{2mV_0^3}}{\hbar eF}\right)$$

- For NV$^-$: Increased tunneling probability from excited ^{3}E state into conduction band for V_g< -9 V
- For NV^0: FNT cannot explain decrease of intensity



Conclusion

- Functional monolithic diamond based field-effect transistor is produced and characterized
- Transistor structure can be used for color center applications

Outlook

- Improvement of growth steps to achieve better electrical properties
- Further investigations of decreasing intensity for NV^0-center for V_g<-9 V
- Implant different color centers, e.g. SiV at a well-defined depth

References

[1] G. Perez et al., Diamond & Related Materials **110**, 108154 (2020)
[2] H. Kawarada, Japanese Journal of Applied Physics **51**, 090111 (2012)
[3] D. Oing et al., Diamond & Related Materials **97**, 107450 (2019)
[4] H. Kawarada et al., Scientific Reports **7**, 42368 (2017)
[5] M. Lenzlinger et al., Journal of Applied Physics **40**, 278 (1969)

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