EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

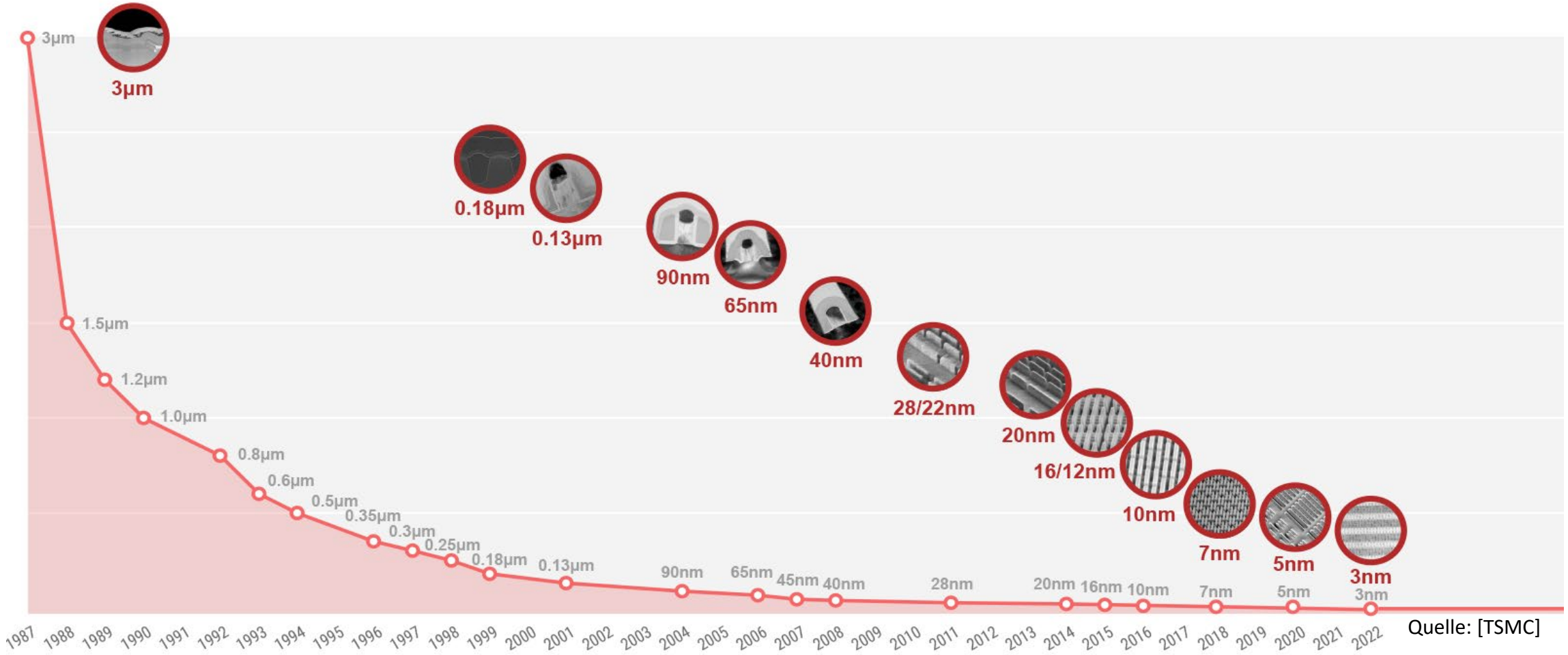
MATHEMATISCH-
NATURWISSENSCHAFTLICHE FAKULTÄT
Kognitive Systeme

Einsatz von Deep Learning zur Erkennung von Messspitzen in Rasterelektronenmikroskopen

BACHELORARBEIT INFORMATIK B. SC. 26. SEPTEMBER 2023

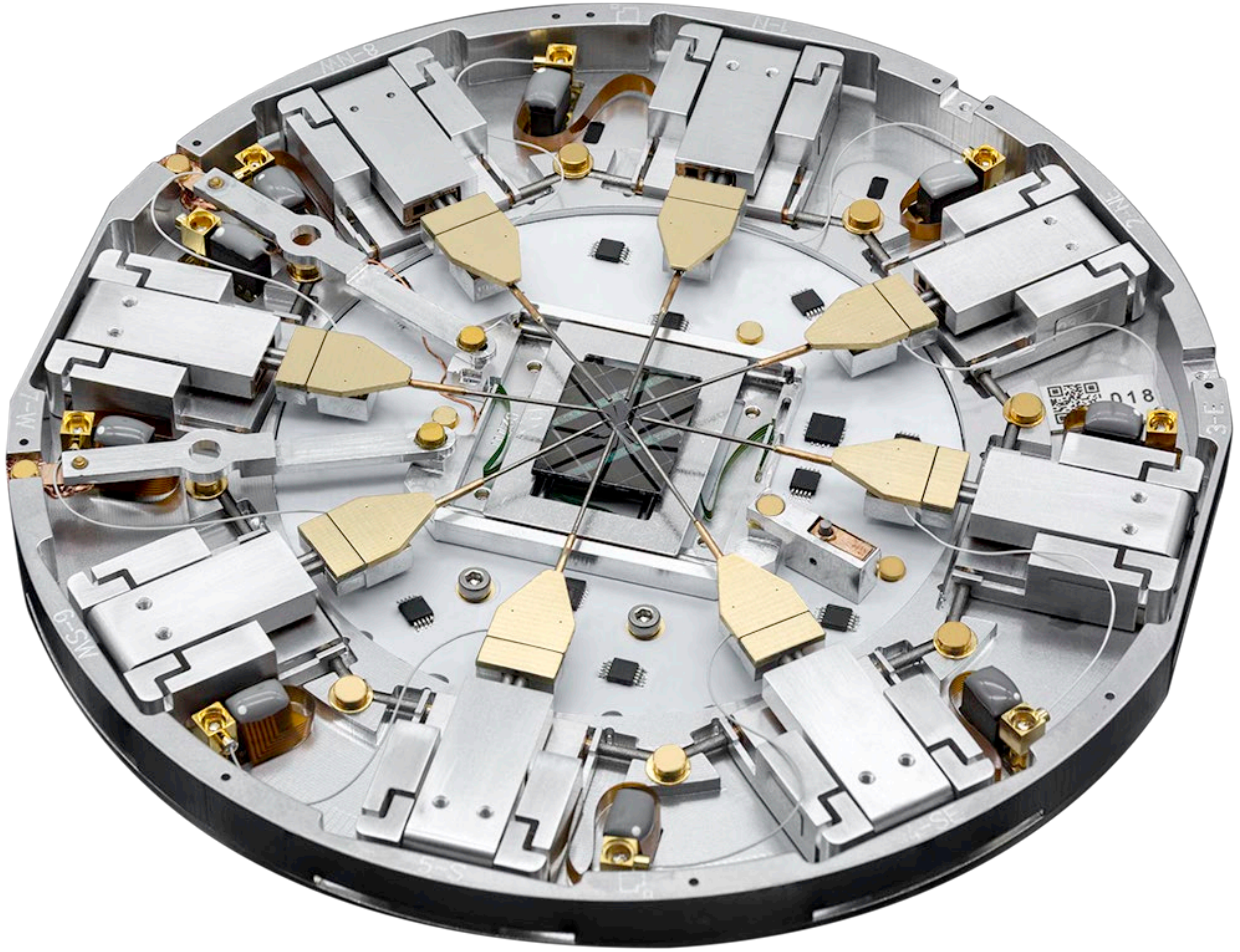
DAVID STEFAN KLEINDIEK

Halbleiter Entwicklung



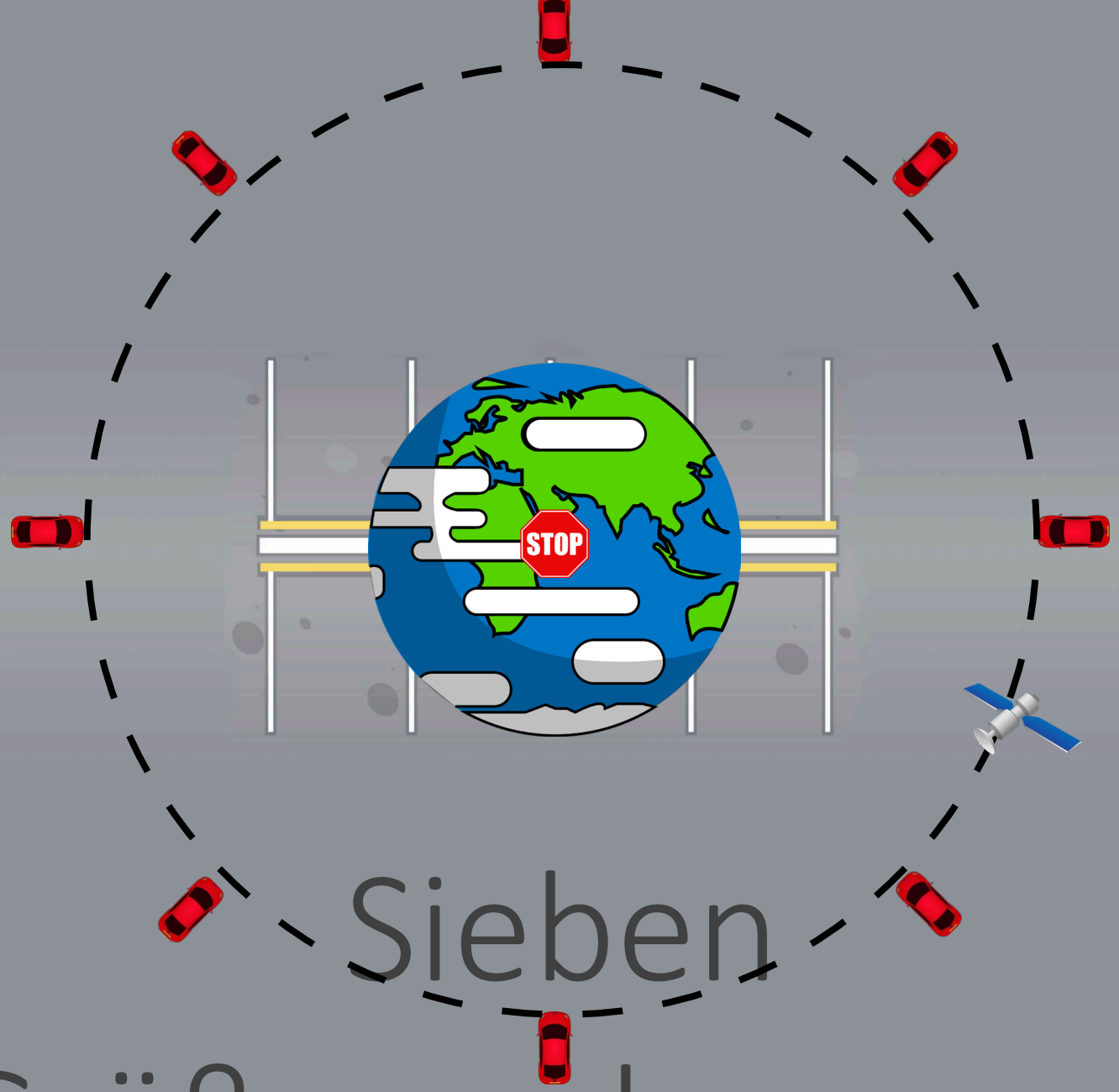
Quelle: [TSMC]

Prober Shuttle (PS8e)



- Fehleranalyse von Transistoren
  - Bis zu acht Manipulatoren
    - Piezomotoren – 0.05 nm Auflösung
    - Zusammenfahren auf 10 µm Radius

kleindiek nanotechnik



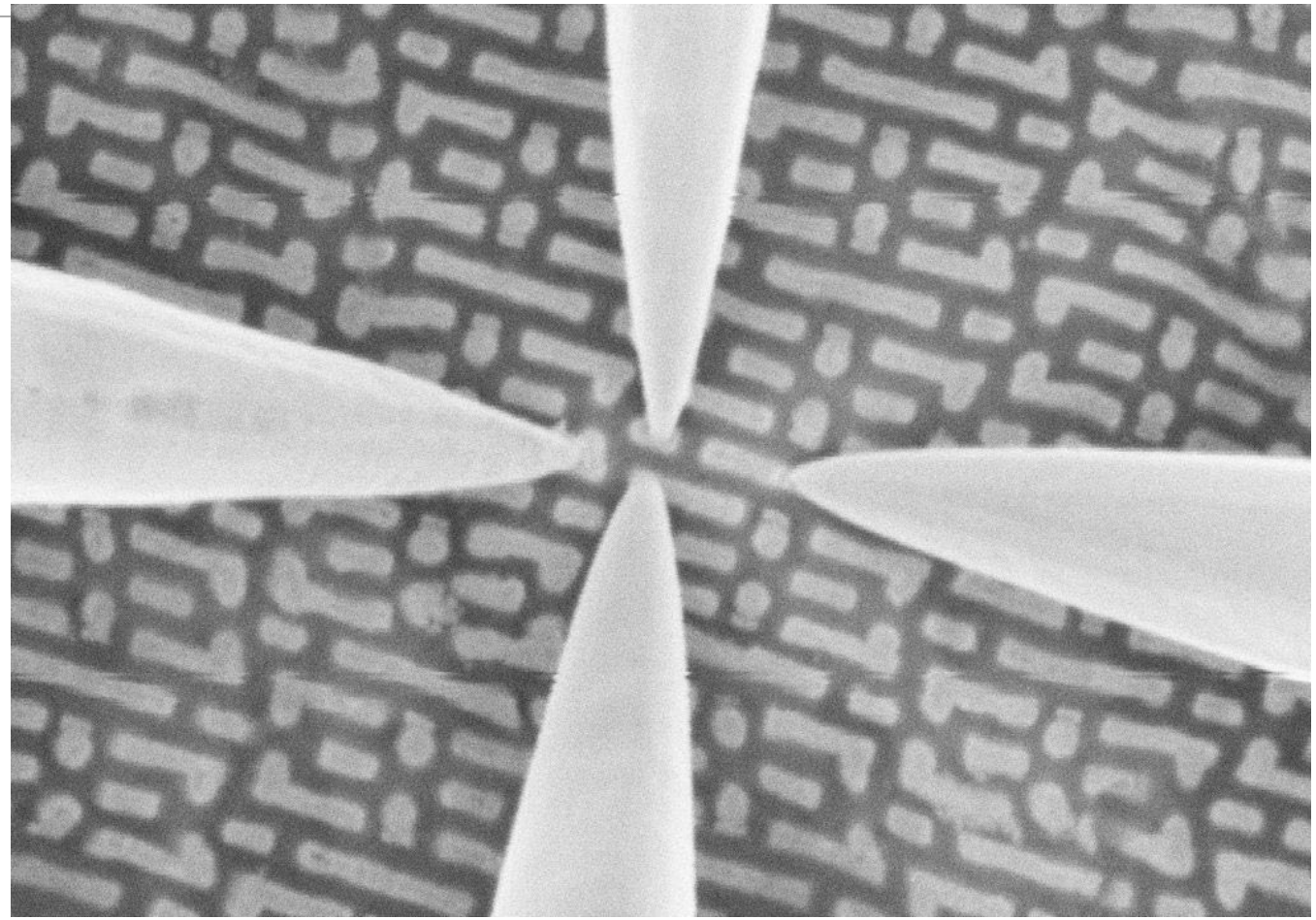
Sieben Größenordnungen!

Forschungsaufgabe

Erkennung:

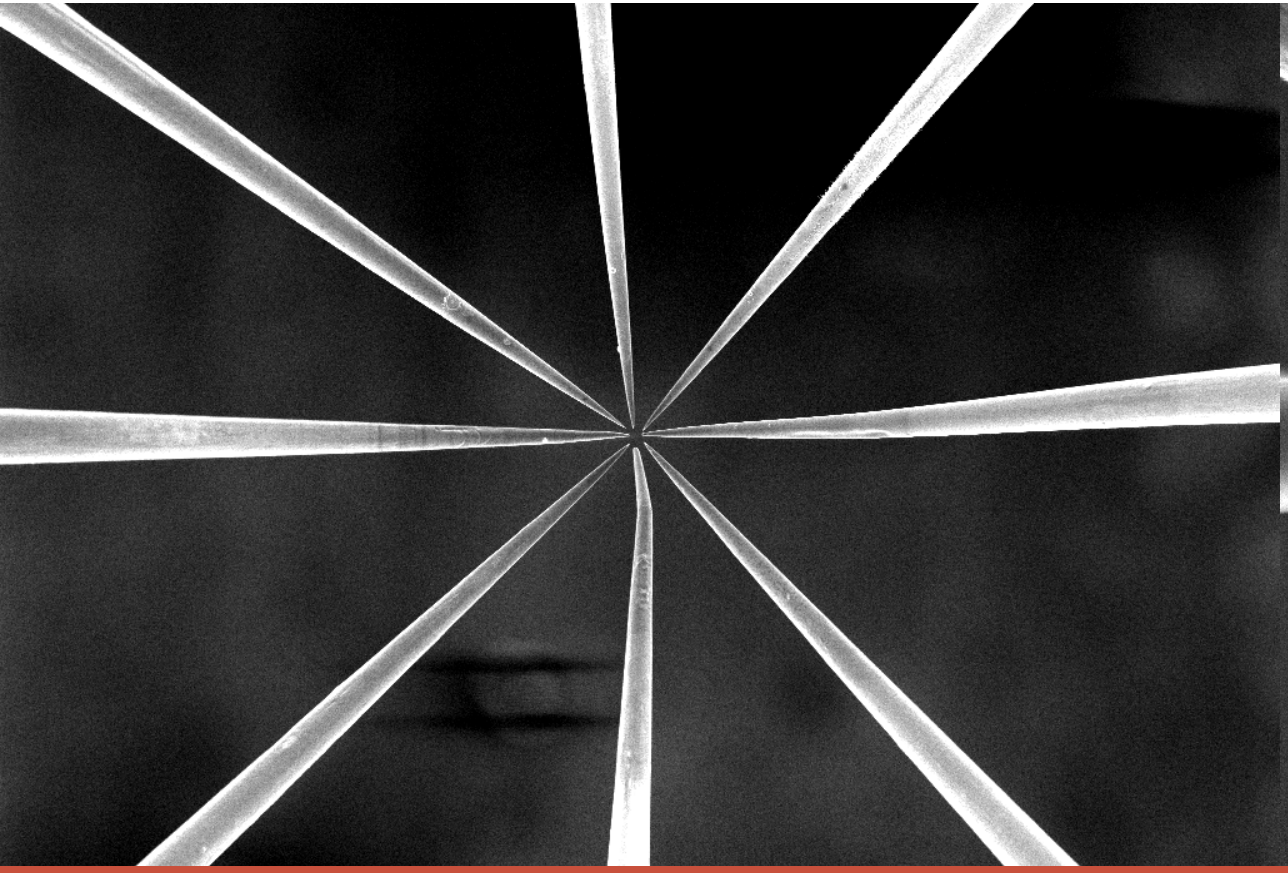
- Position der Messspitze
- Bildbereich mit Messpitze

➢ Deep Learning Modelle



Vergrößerung

2.000-fach



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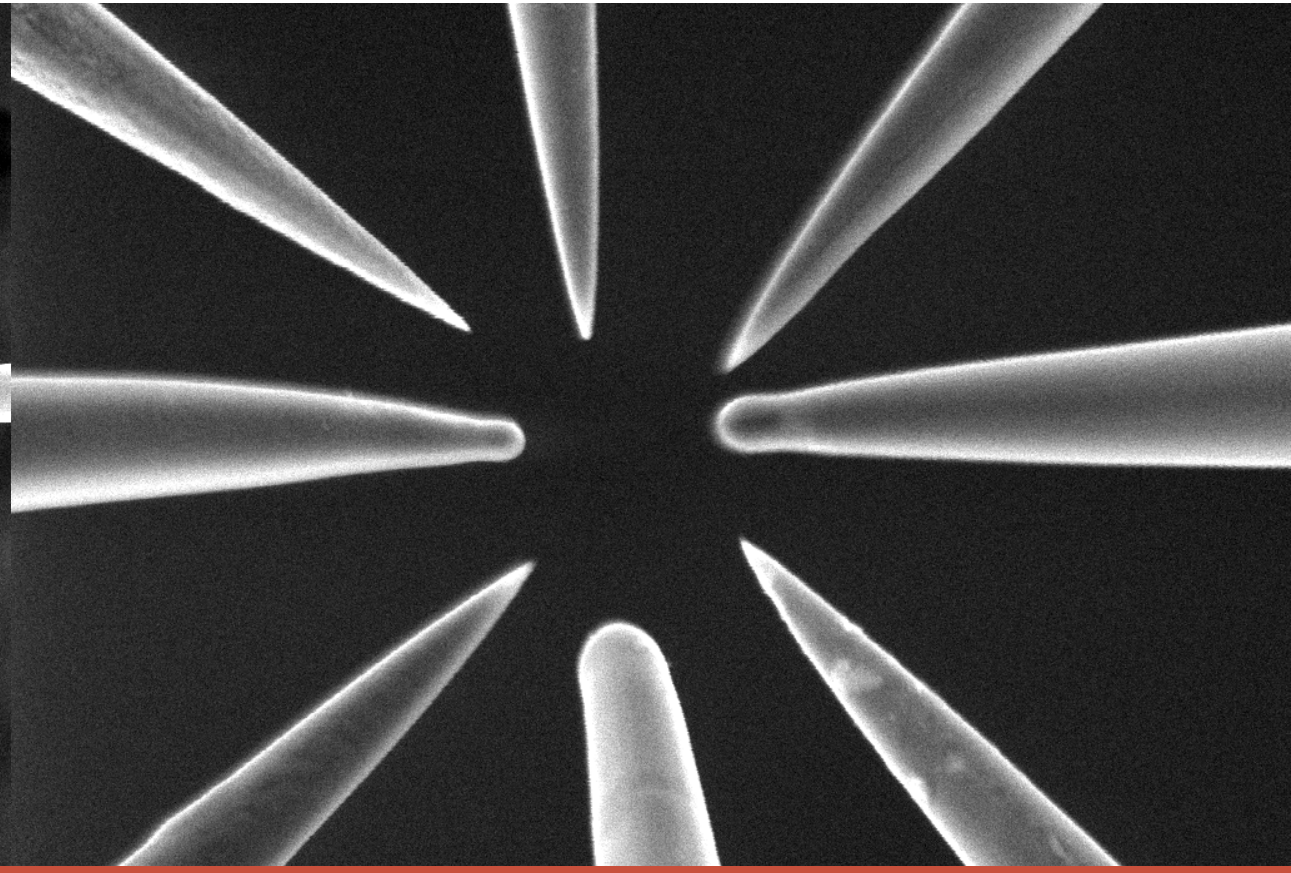
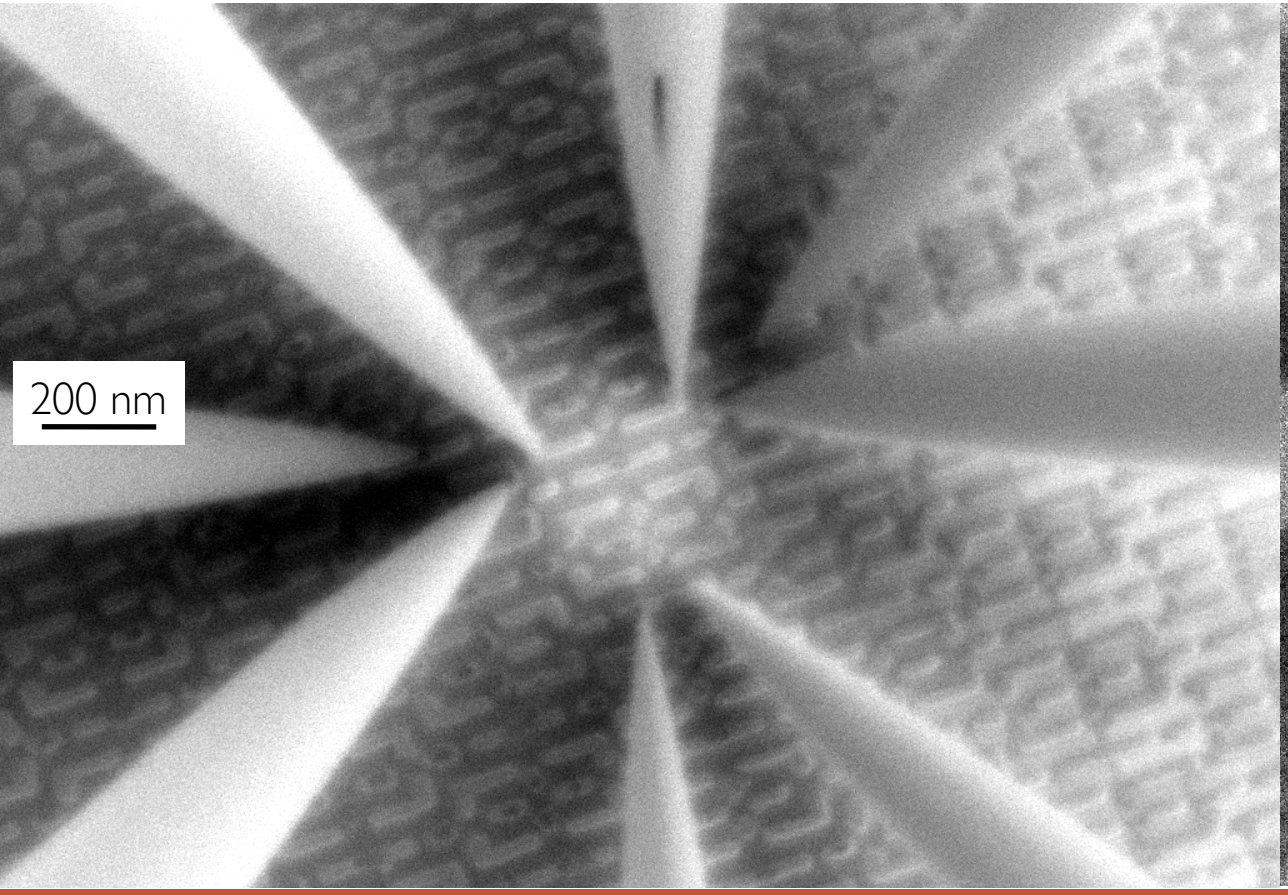
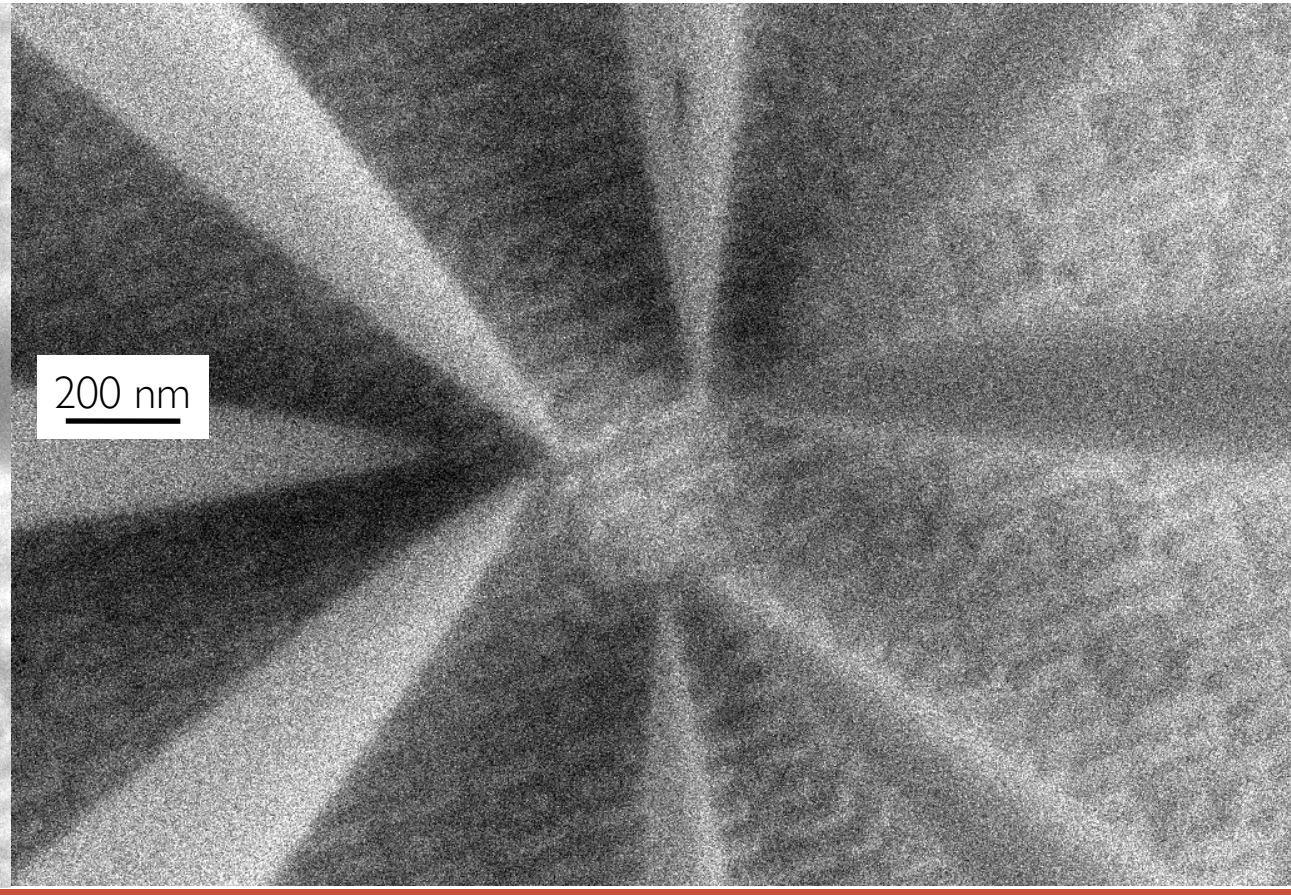


Abtastrate

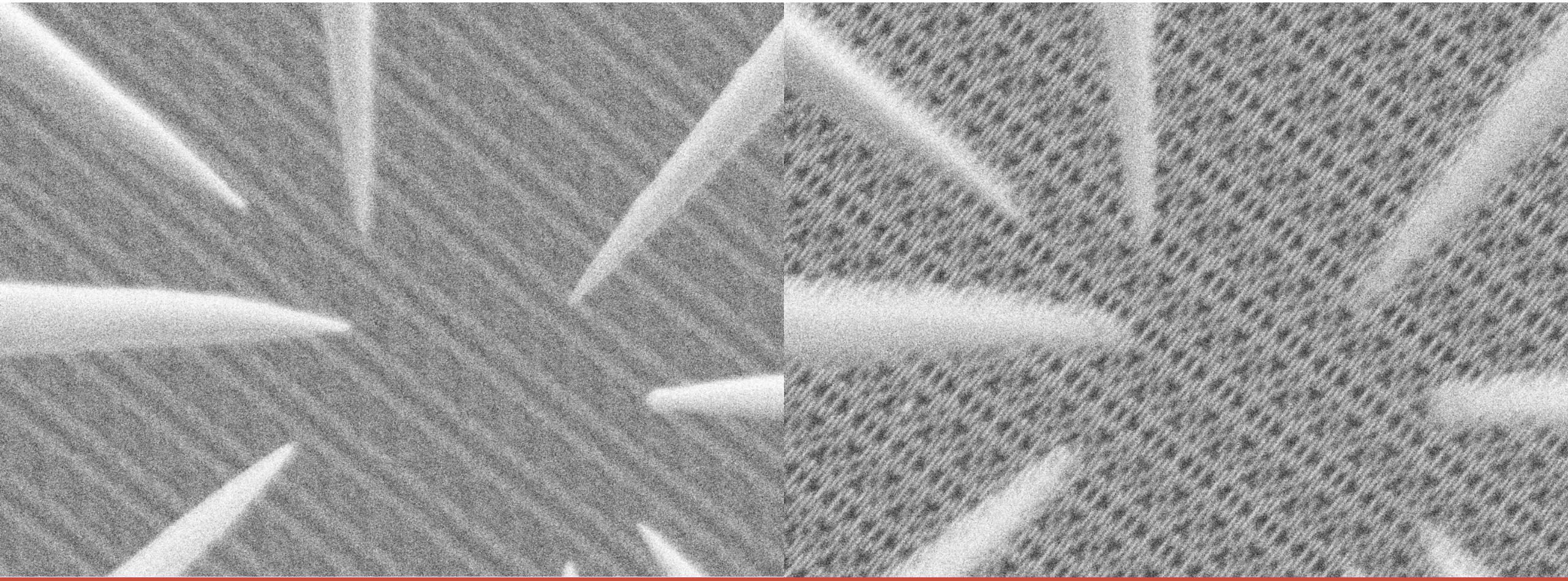
20 s



<1 s

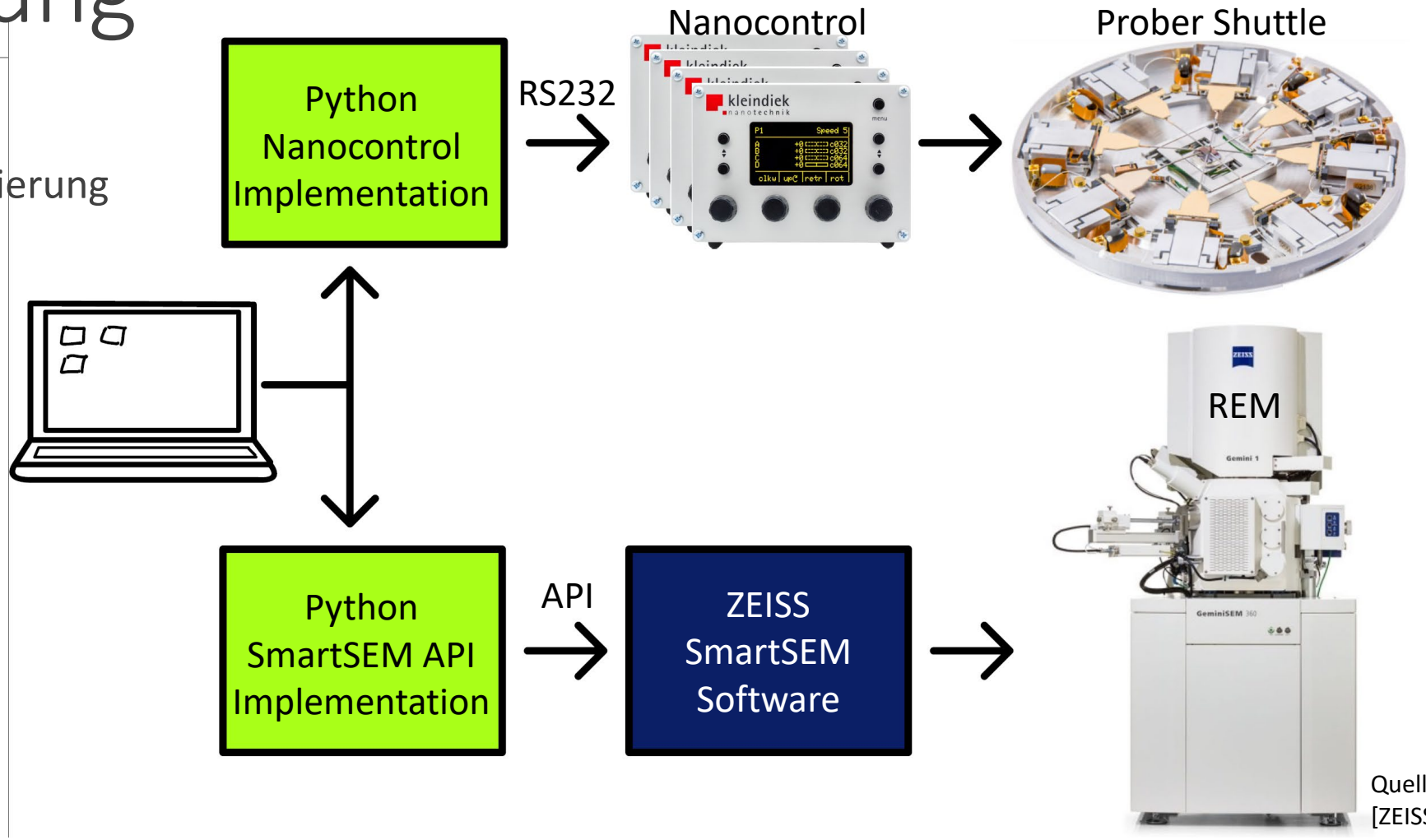


Fokus



Ansteuerung

- Vereinte Ansteuerung
- Skripte zur Automatisierung

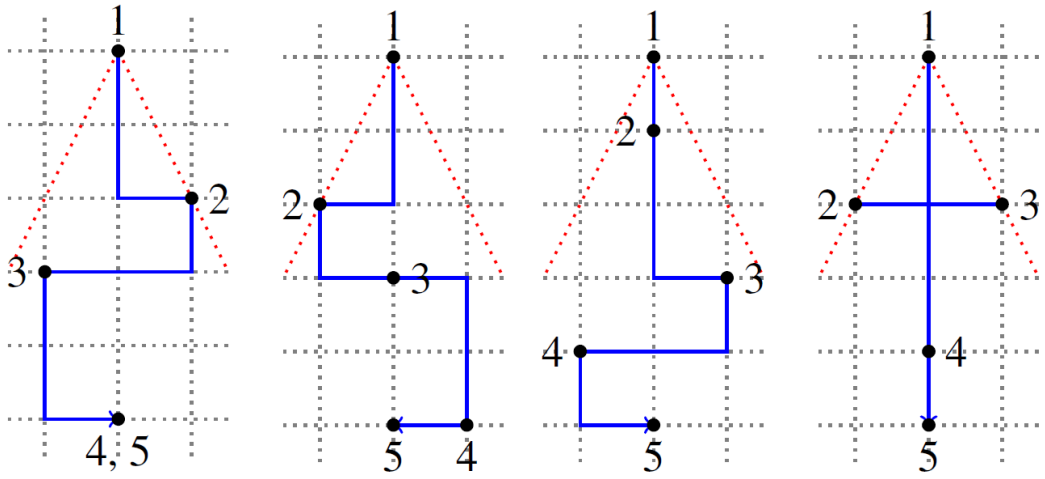


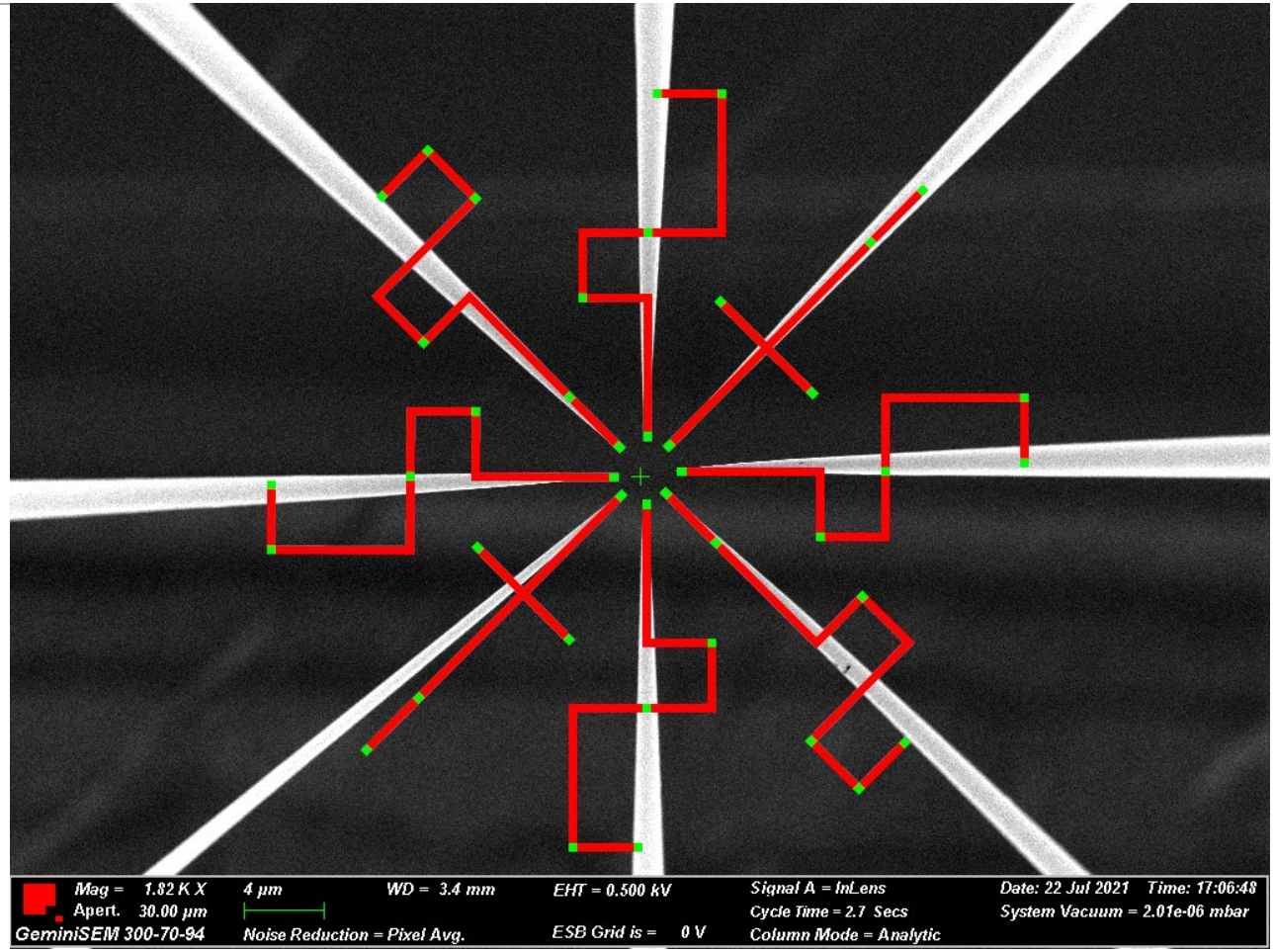
Quelle: [ZEISS]

Anforderungen Datensatz

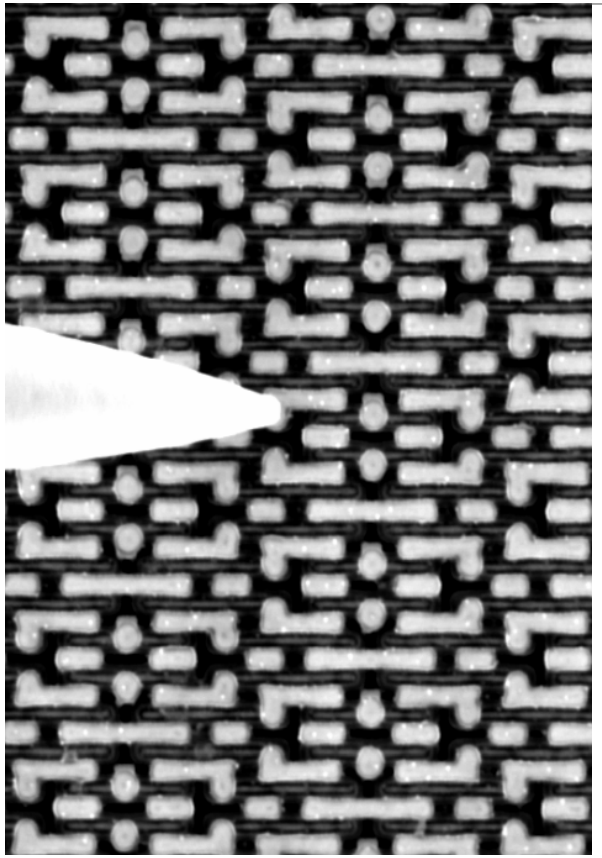
Variation der Spitzenposition

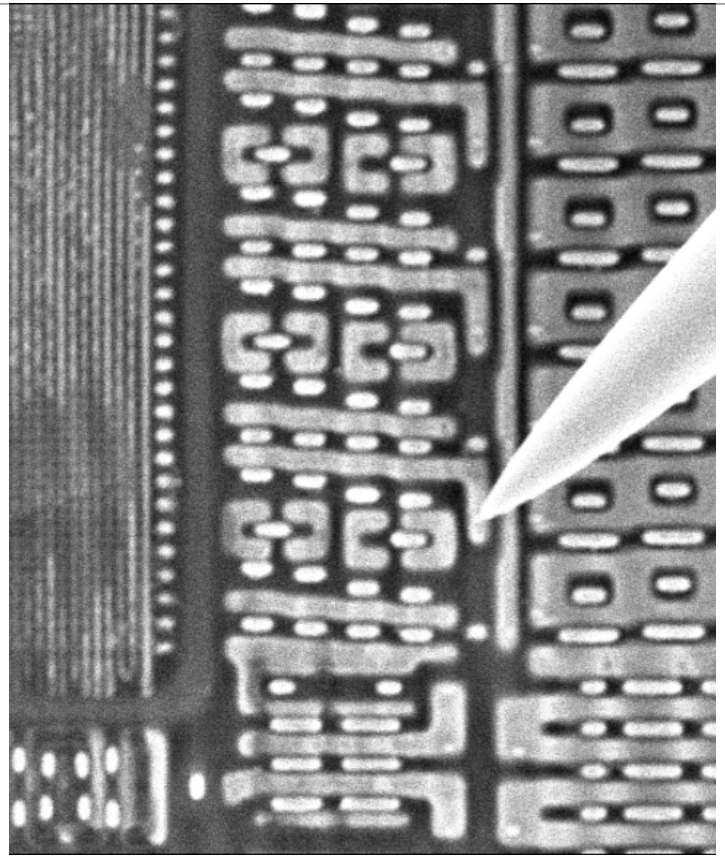
- Vordefinierte Pfade
- Keine Kollision der Spitzen → 45 Grad
- Anfahren von 5 Positionen
- Skaliert mit Vergrößerung
- zufällige Zuweisung

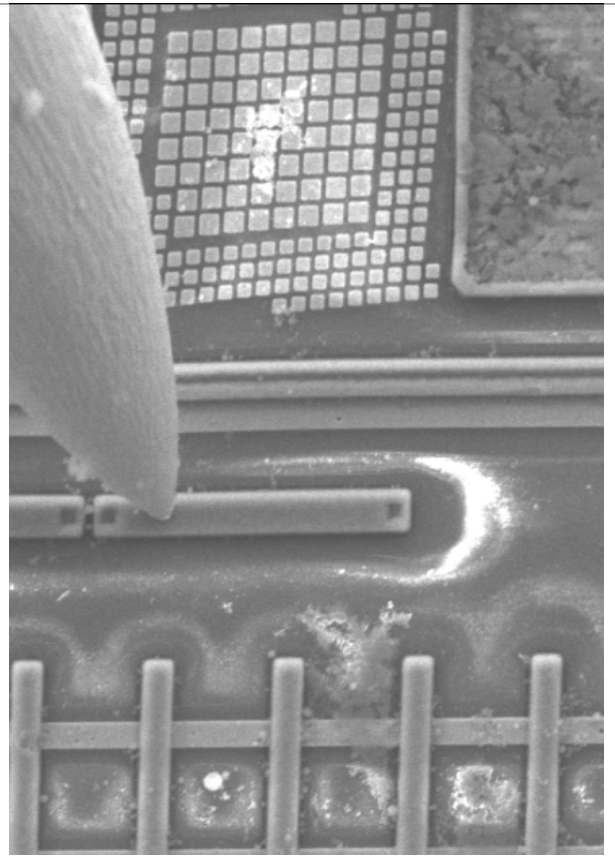




Strukturunterschiede





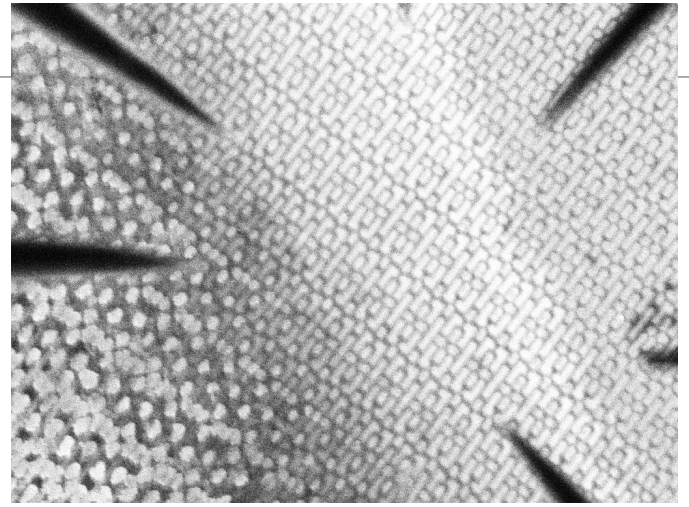
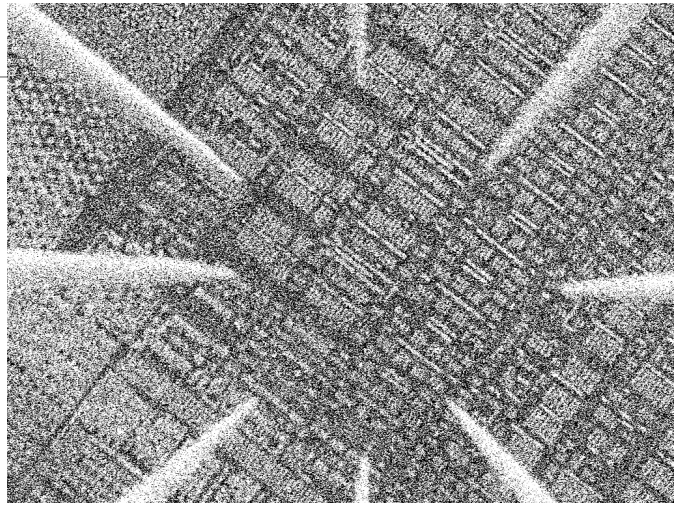
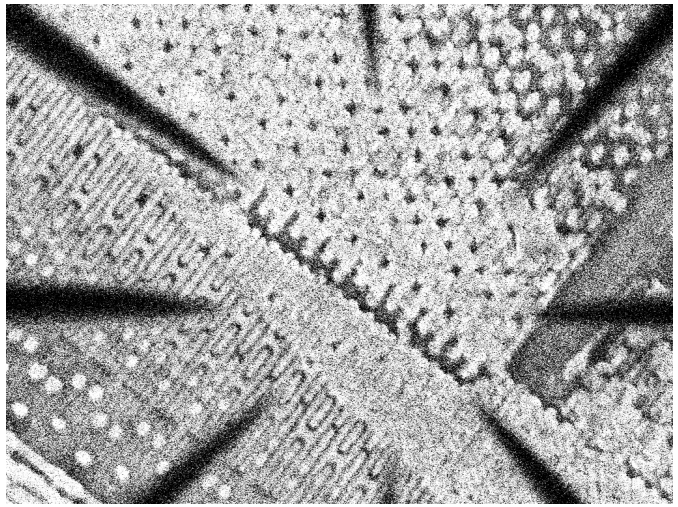
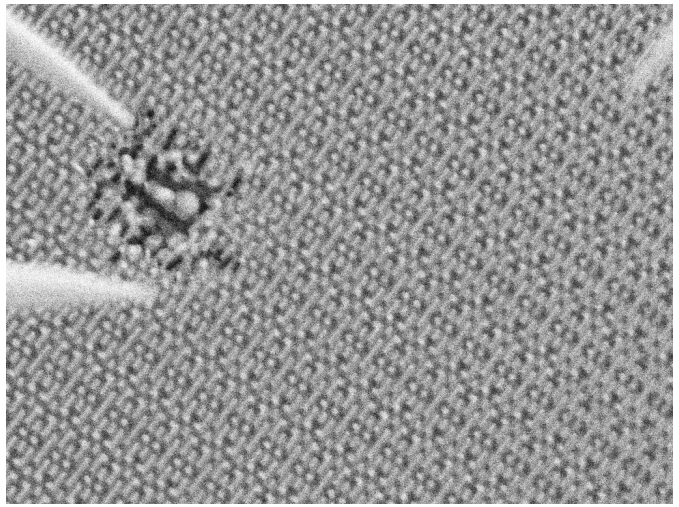
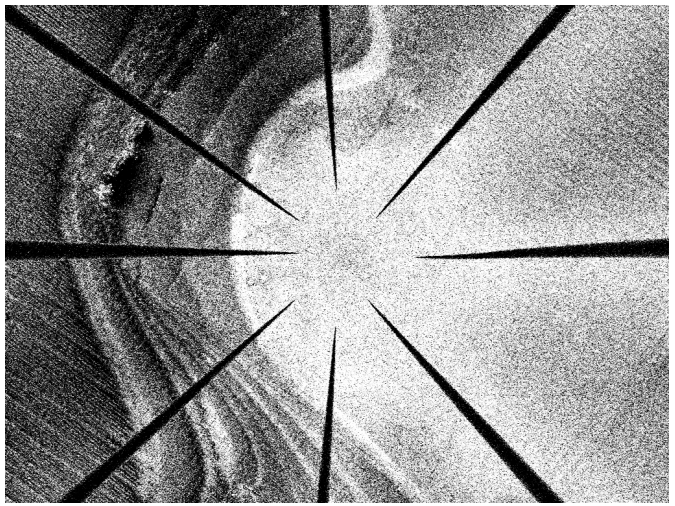


→ Probe zwischen Bildern verfahren

Aufnahme

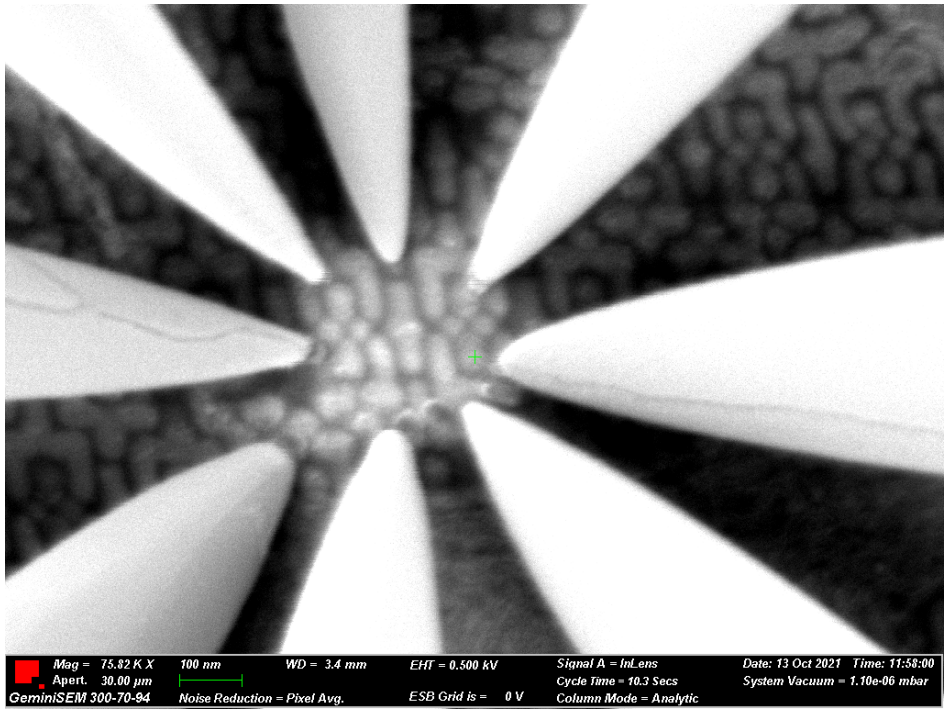
- 4 Vergrößerungstufen
  - 5 Spitzenpositionen
    - 5 Bildparameter

→ 100 Bilder / Durchlauf

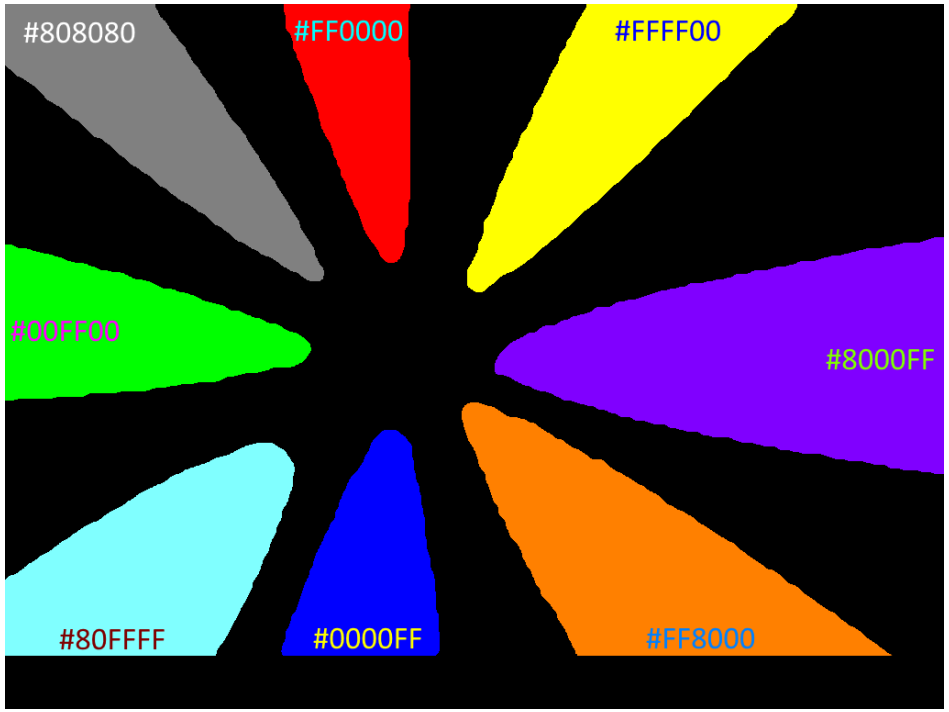






Datenannotation

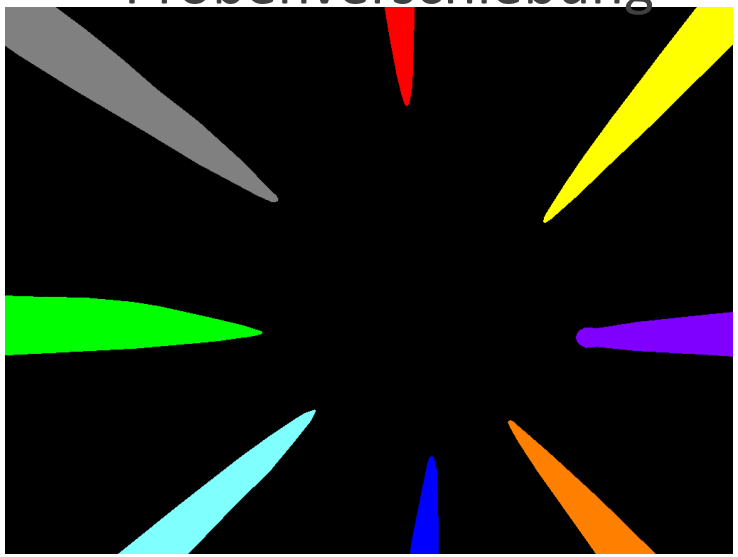
- Manuelles einfärben der Spitzen
- Photoshop + Nachbearbeitung

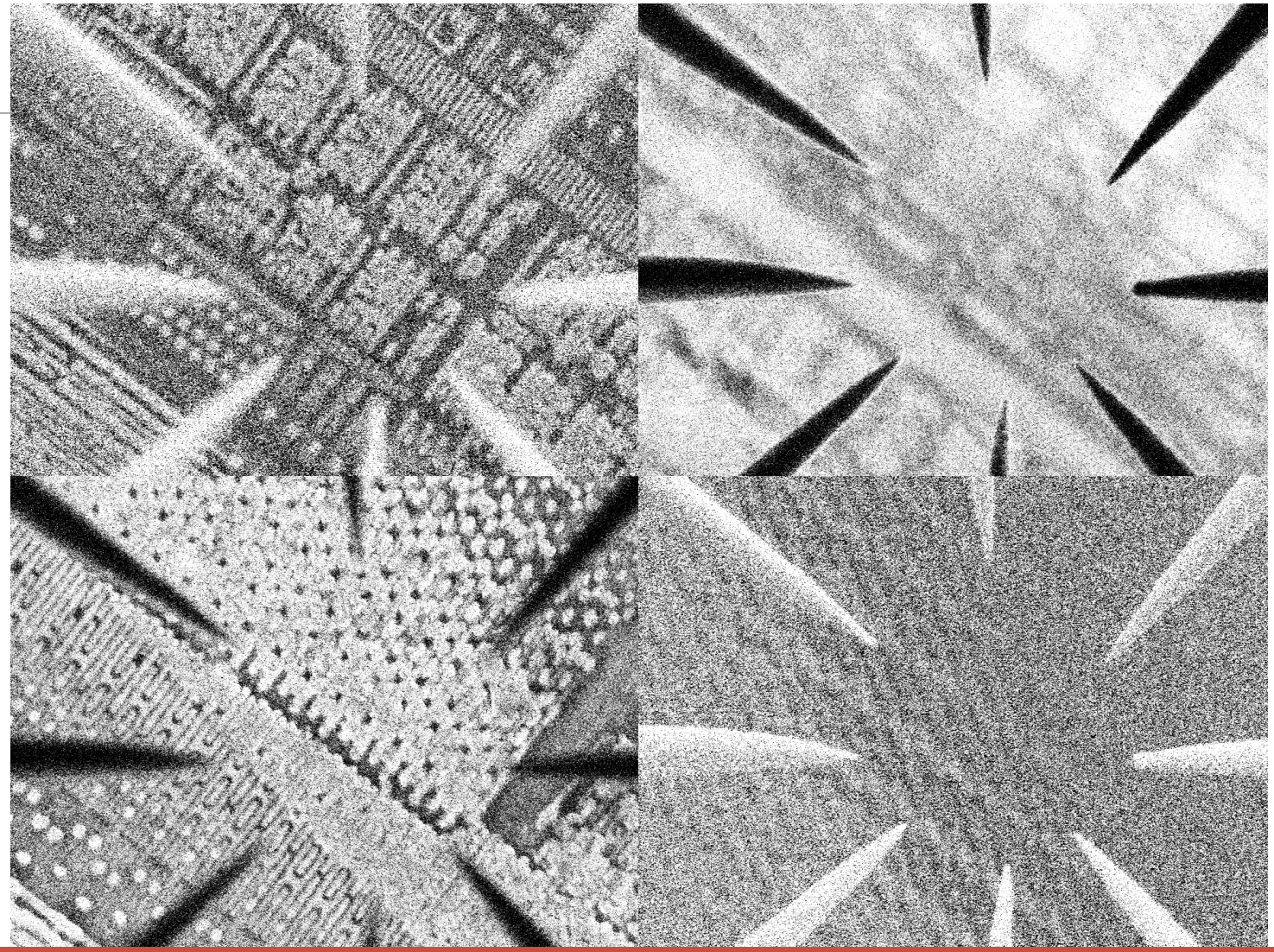


- Universelles Format, schnelle Konvertierung



- 1 Maske → 5 Bilder
- Parametervariation
- Probenverschiebung





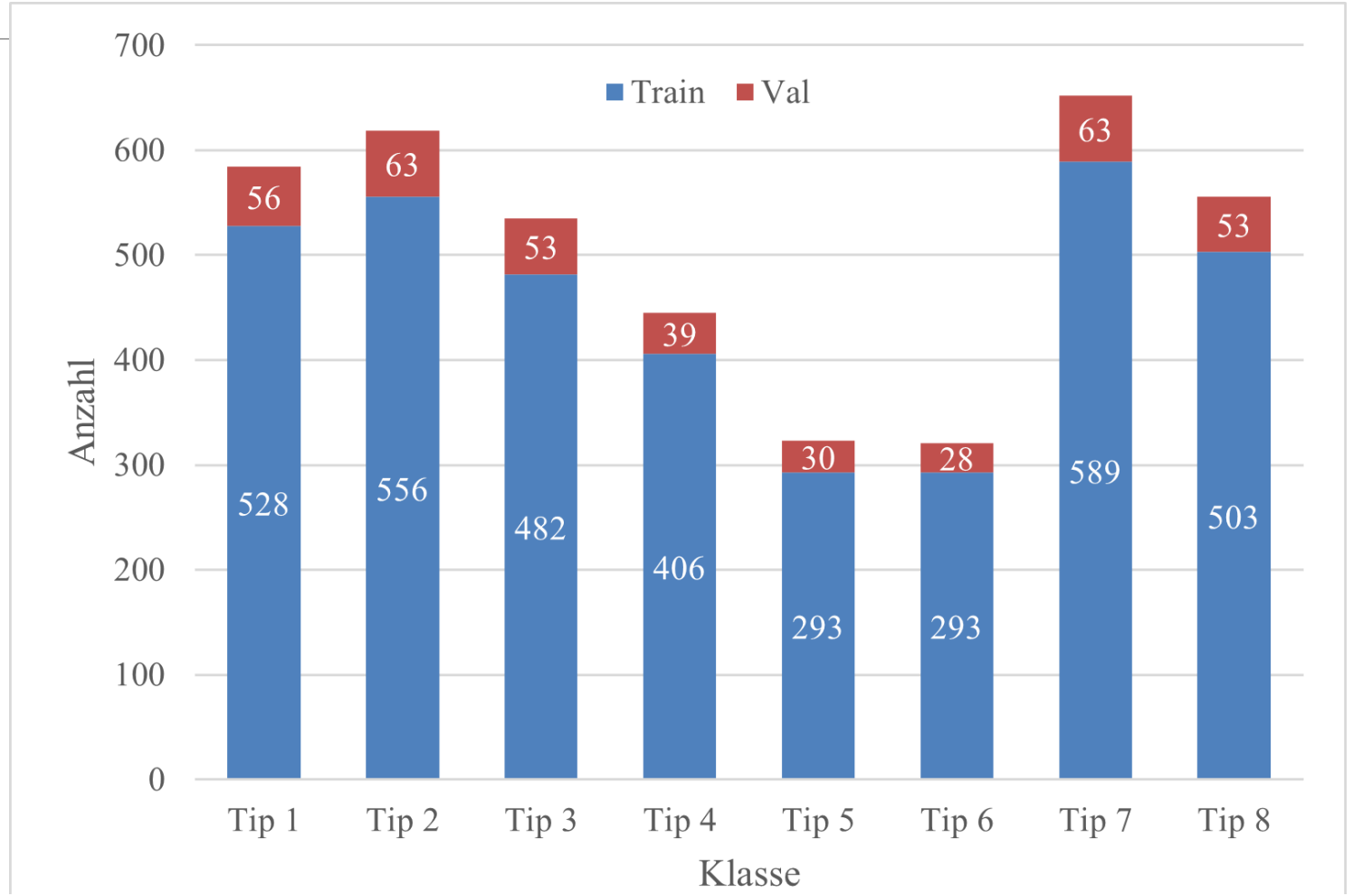
Datensatz

- 750 Bilder

  150 aus Einsätzen

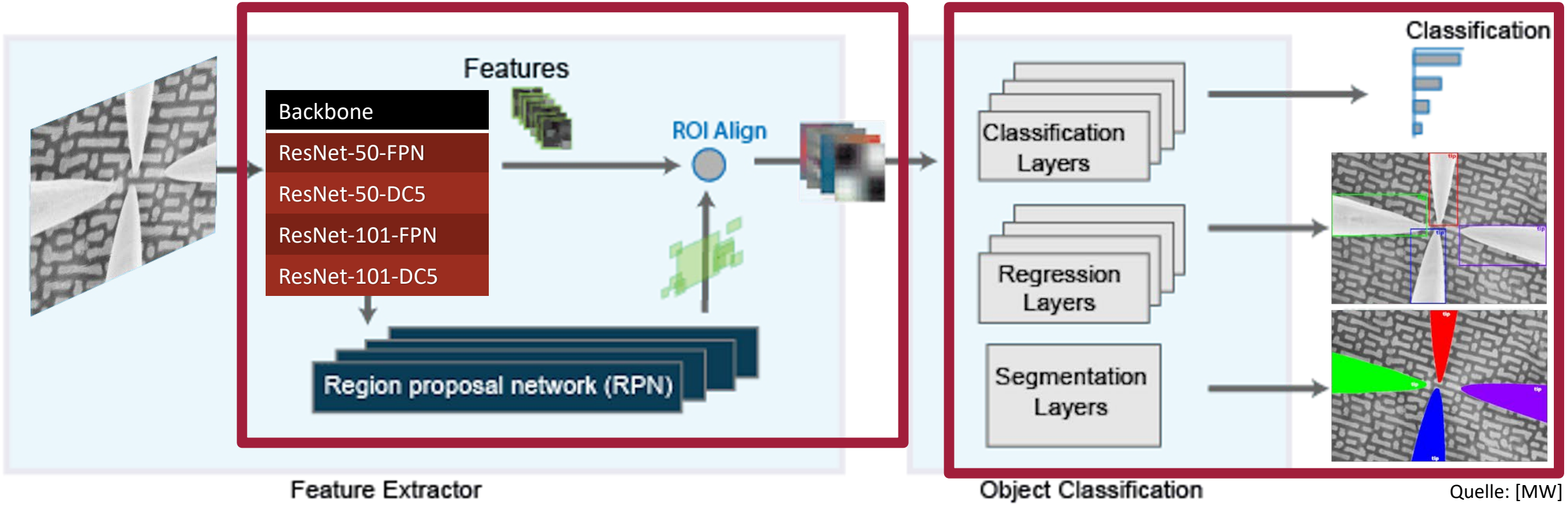
  600 per Routine erstellt
- 90% Training

  10% Validierung
- Nicht gleichverteilt



Mask R-CNN

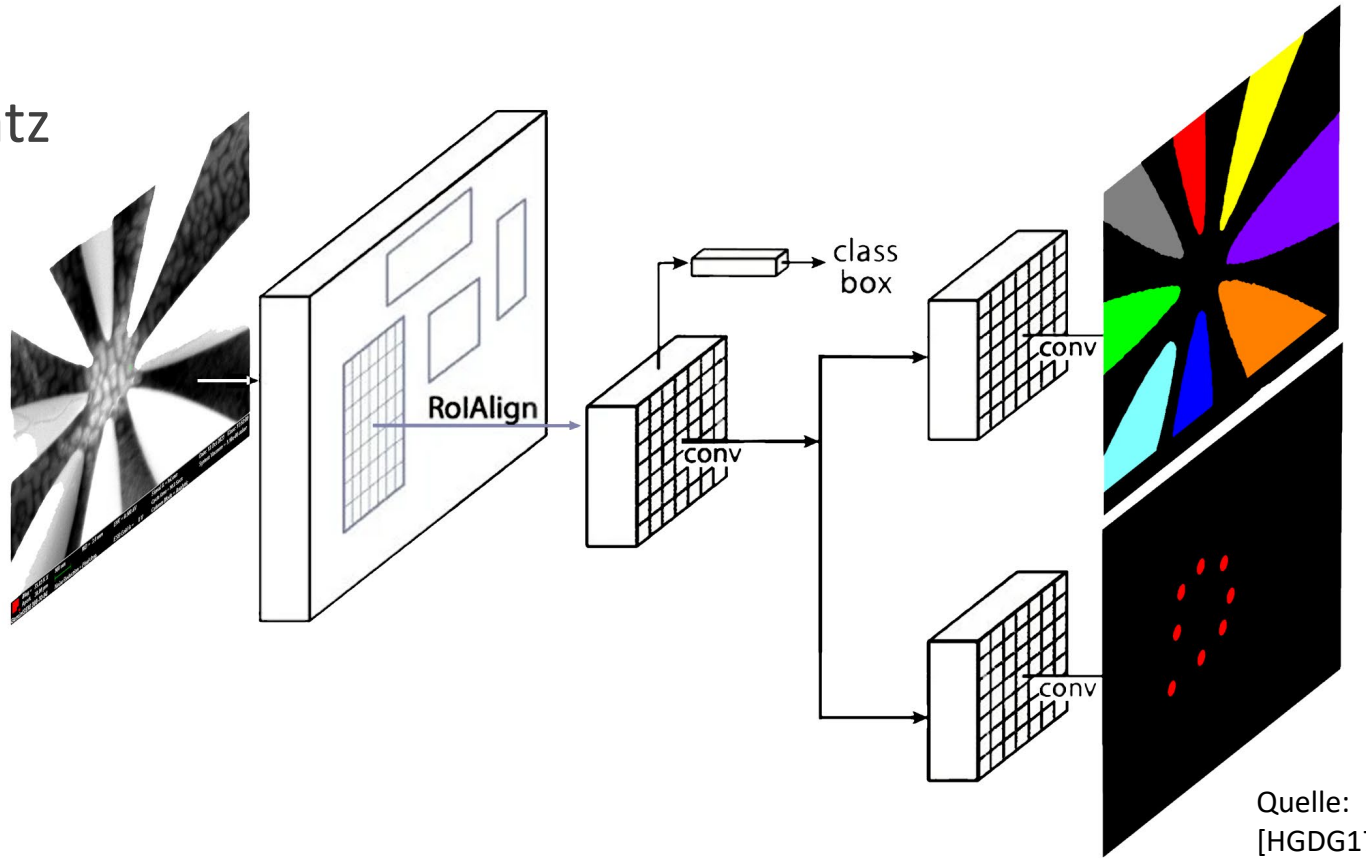
- Zweistufiges Netz



Quelle: [MW]

Mask/Keypoint R-CNN

- Keypoint und Maske vereint
- Vortrainiert auf COCO Datensatz
- Detectron2 Framework



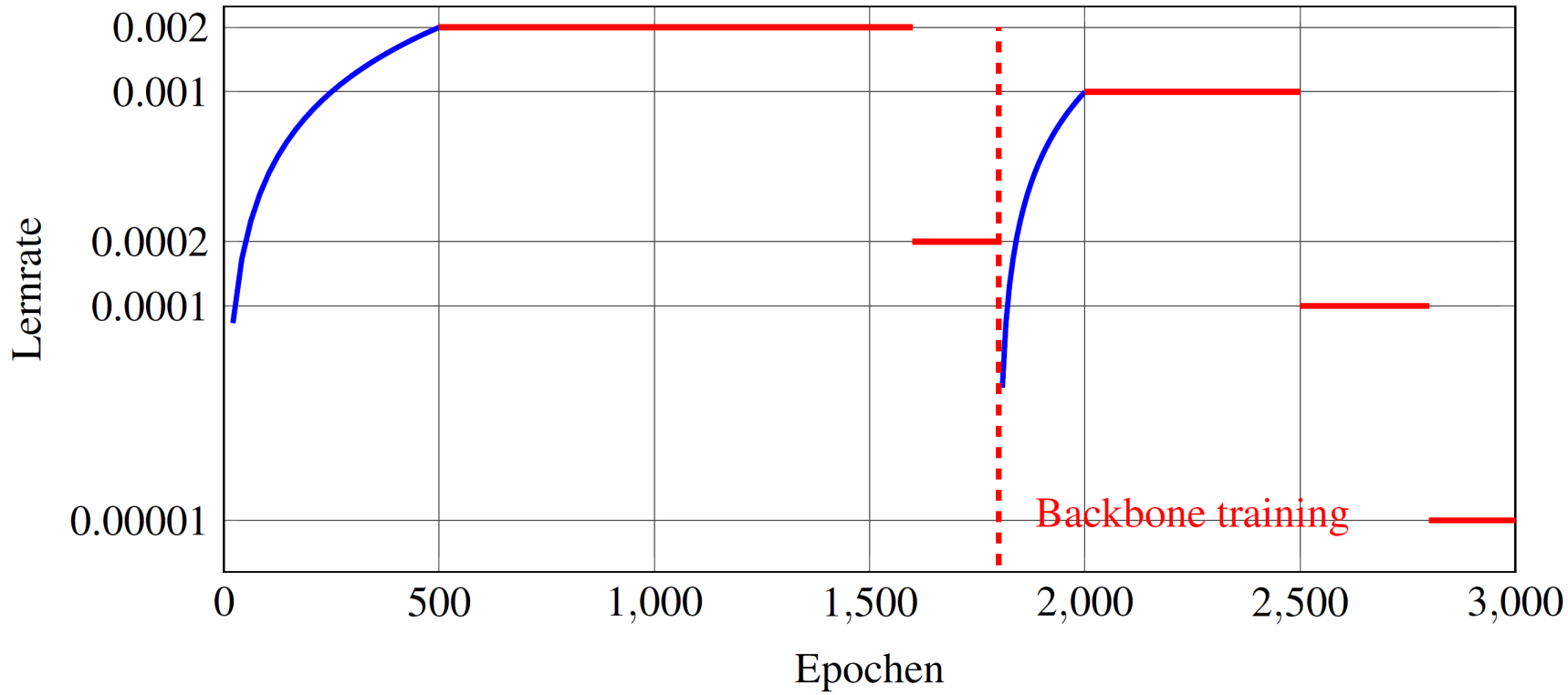
Quelle:
[HGDG17]

Hyperparameter

- Lernrate
- Momentum
- Decay
- Batch-Größe

- Zweistufiges Training

  Maskenkopf → Backbone



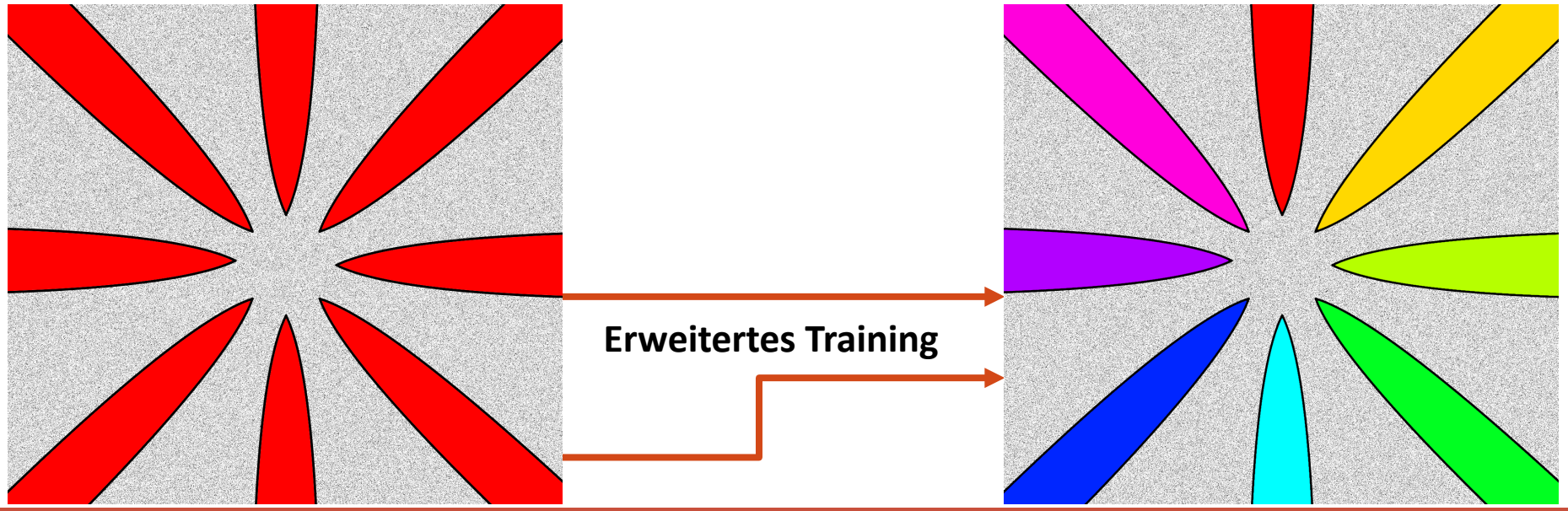
Modellvarianten

SINGLE CLASS VARIANTE

- Alle Messspitzen als eine Klasse behandelt

MULTI CLASS VARIANTE

- Messspitzen nach Richtung unterschieden
- 8 Spitzen → 8 Klassen



Ergebnisse

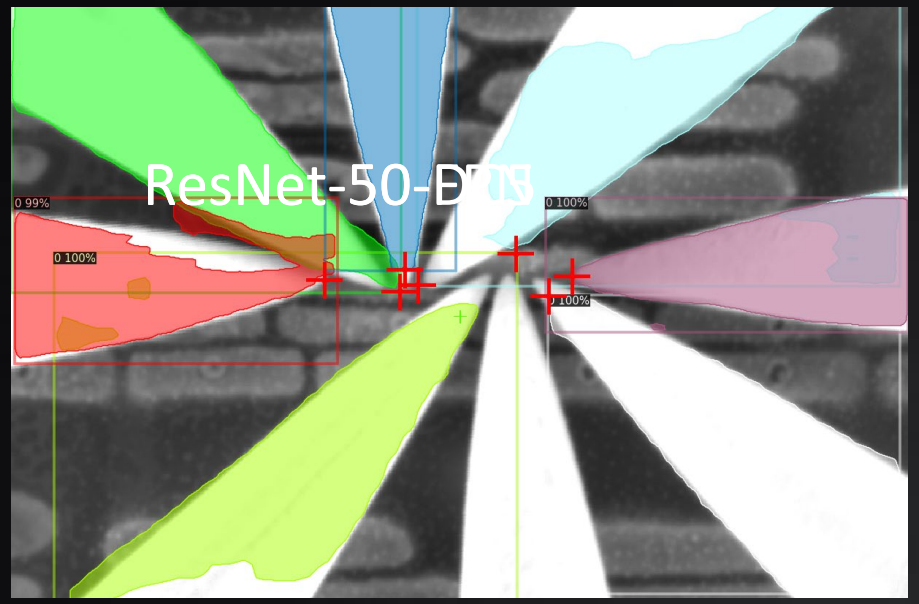
MODELLLEISTUNG

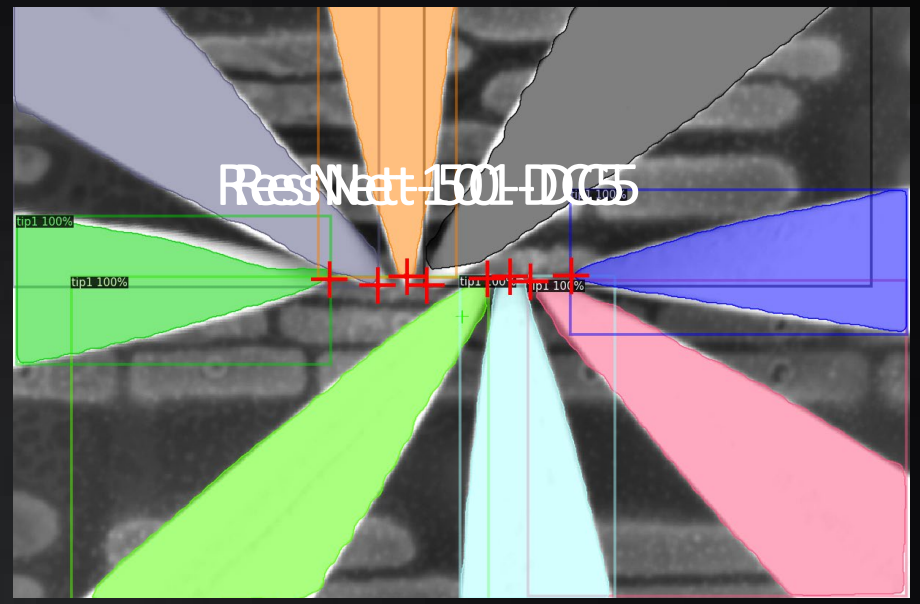
Feature Pyramid Network (FPN)

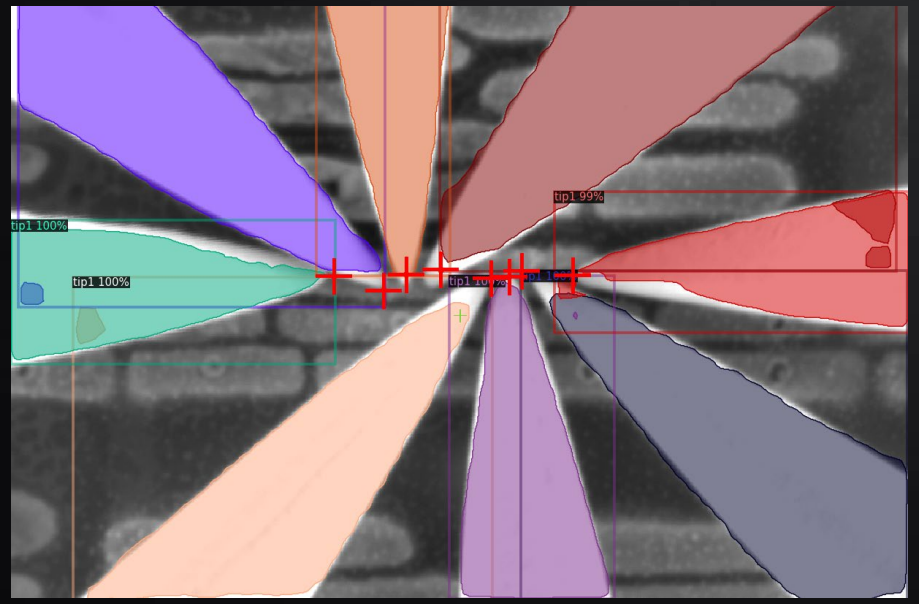
Dilated Convolution (DC5)

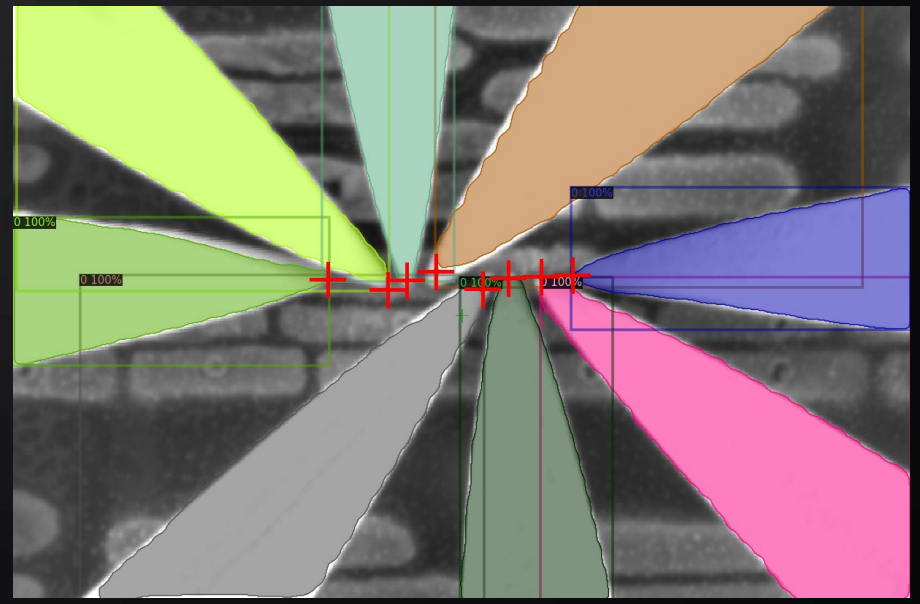
ResNet-50

ResNet-101









Modellleistung: Average Precision

KEYPOINT ERKENNUNG

$AP^{OKS=.75}$	FPN	DC5
R-50	90.79	95.08
R-101	93.34	**95.34**

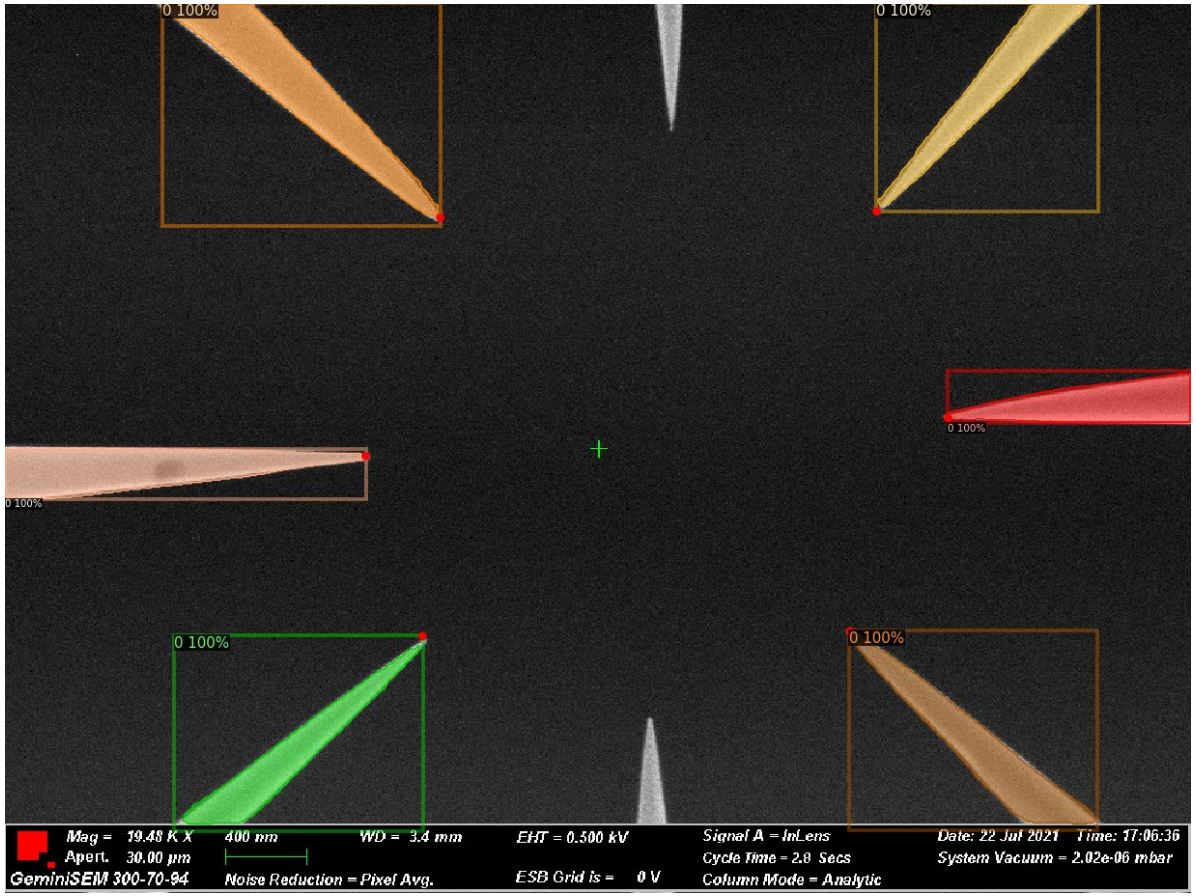
SPITZEN SEGMENTIERUNG

$AP^{IoU=.75}$	FPN	DC5
R-50	46.08	**60.23**
R-101	51.01	59.24

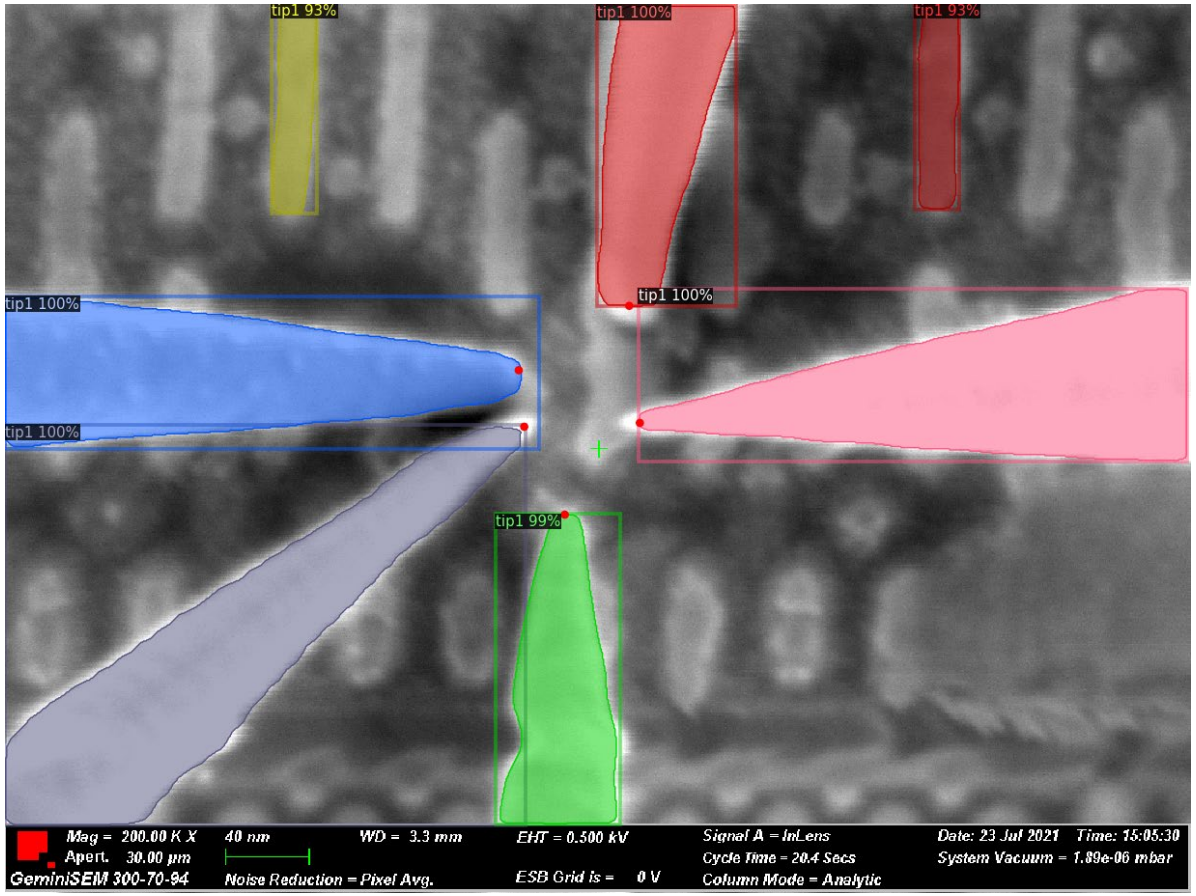
Konfidenzschwellwert = 90%

Modellleistung: FN-/FP-Rate

R50-DC5 @99% Konfidenz



R50-DC5 @90% Konfidenz



Modellleistung: FN-/FP-Rate

FALSCH NEGATIV

FN-Rate	FPN	DC5
R-50	0.094	0.082
R-101	0.094	**0.078**

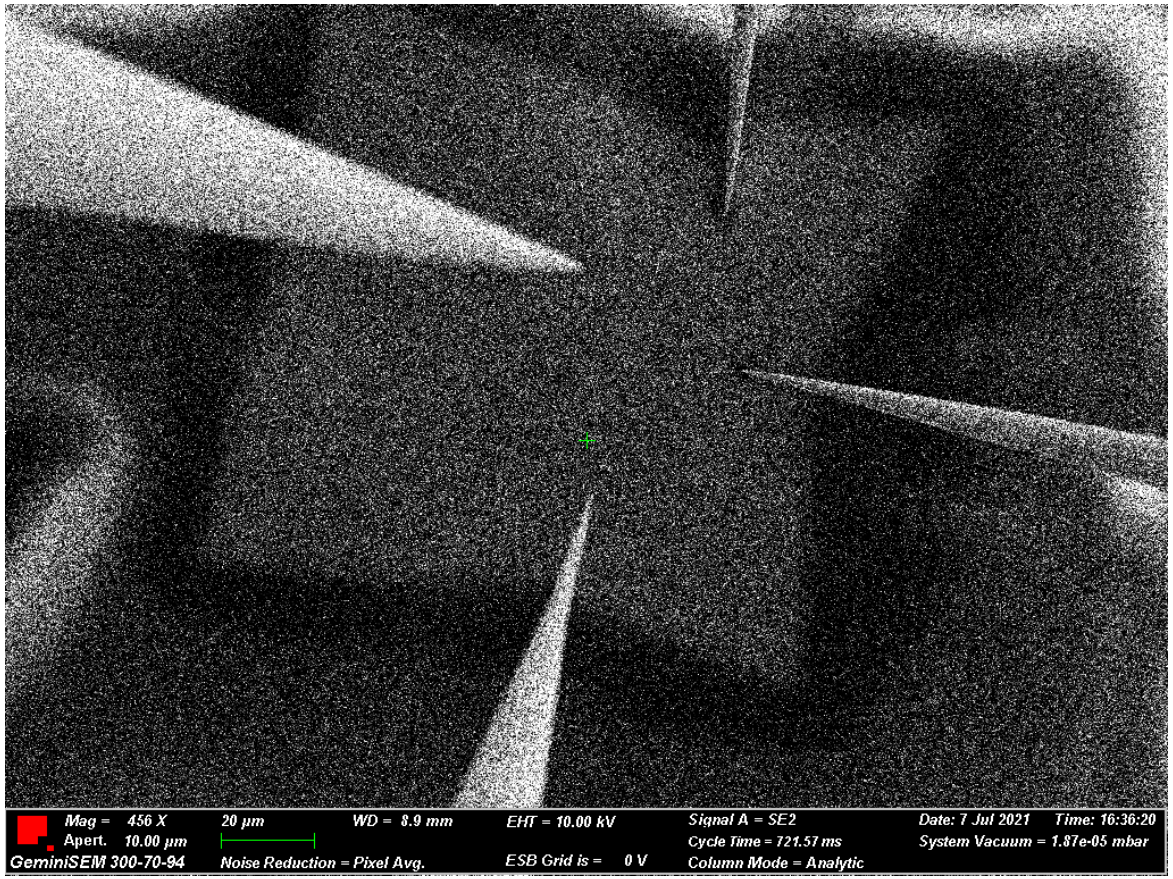
FALSCH POSITIV

FP-Rate	FPN	DC5
R-50	0.060	0.043
R-101	0.054	**0.039**

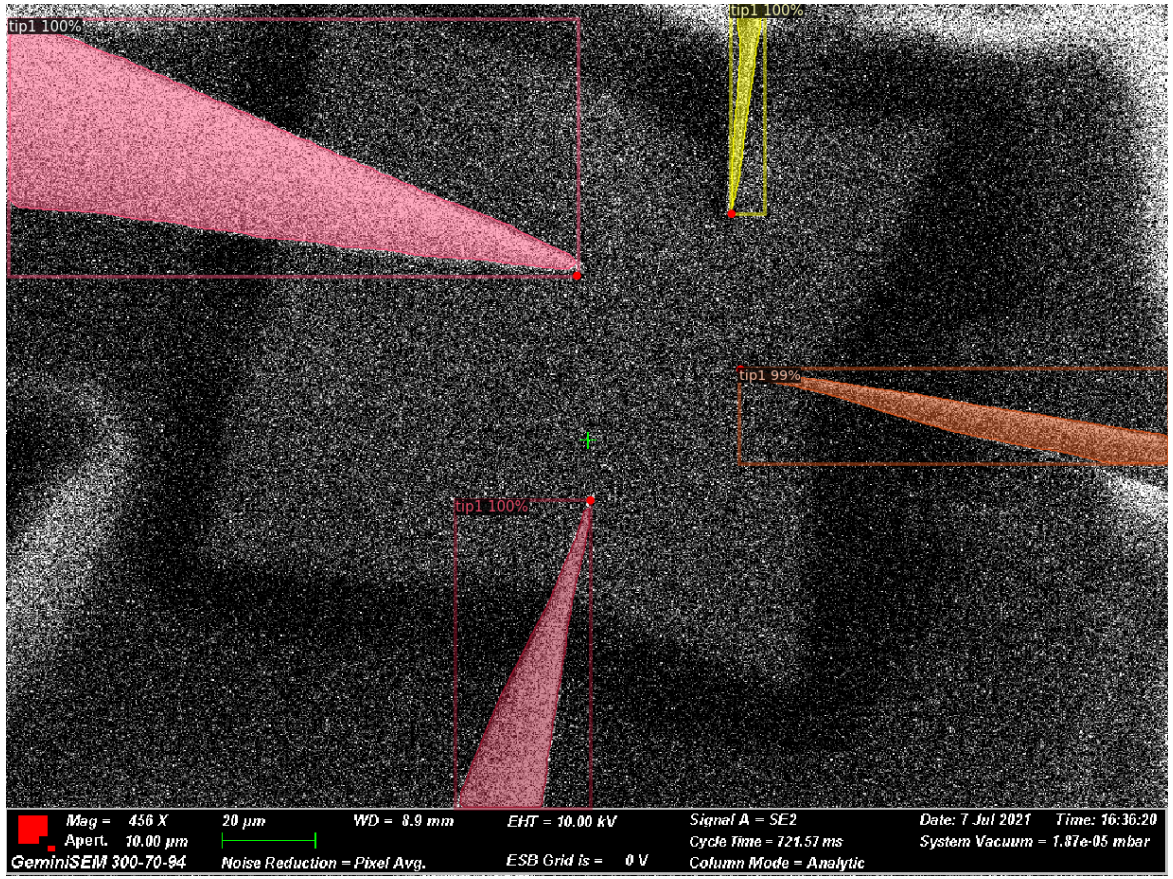
Konfidenzschwellwert = 90%

Form- und Rauschresistenz

Original



R50-DC5

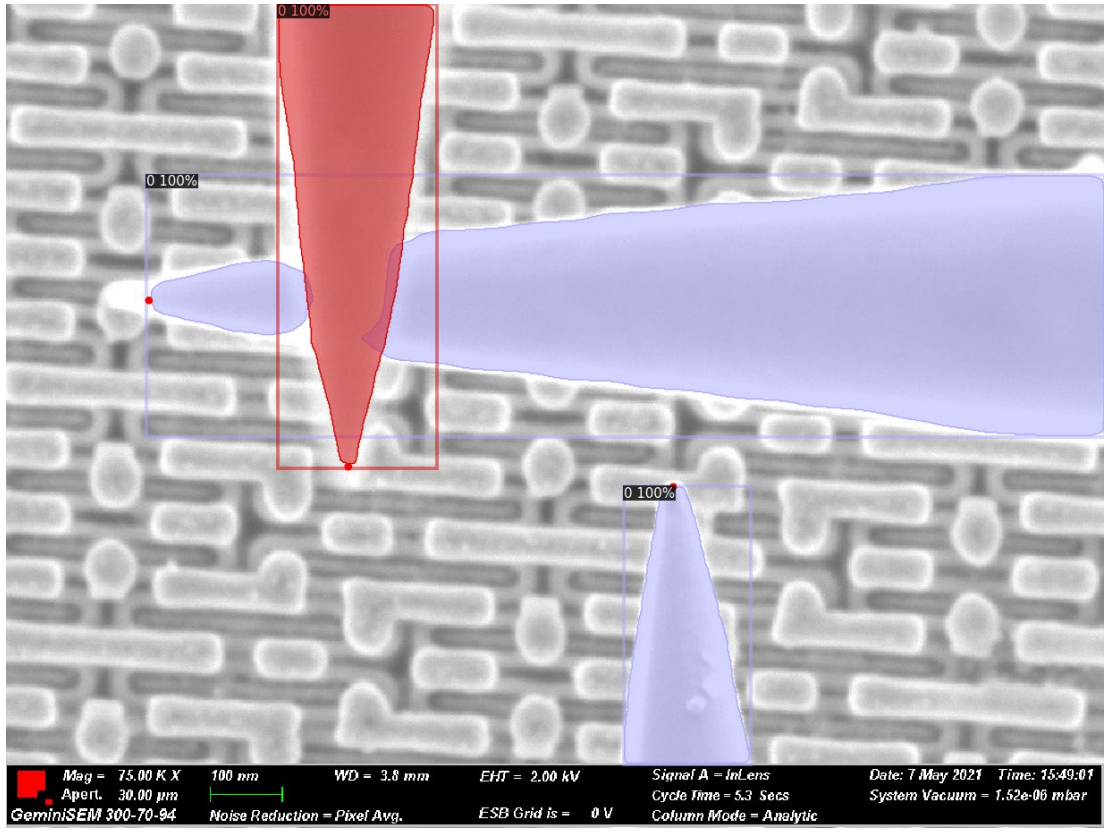


Herausforderung

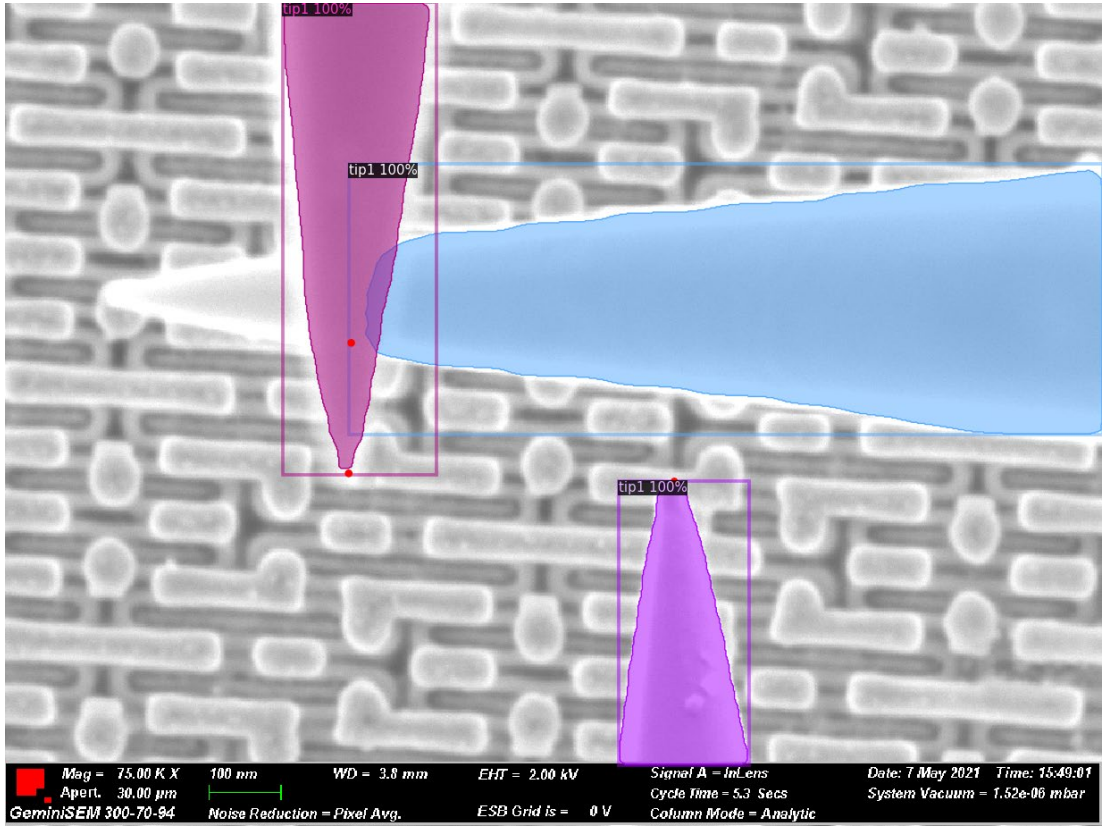
SEGMENTIERUNG

Problem: Überlappung

R50-DC5

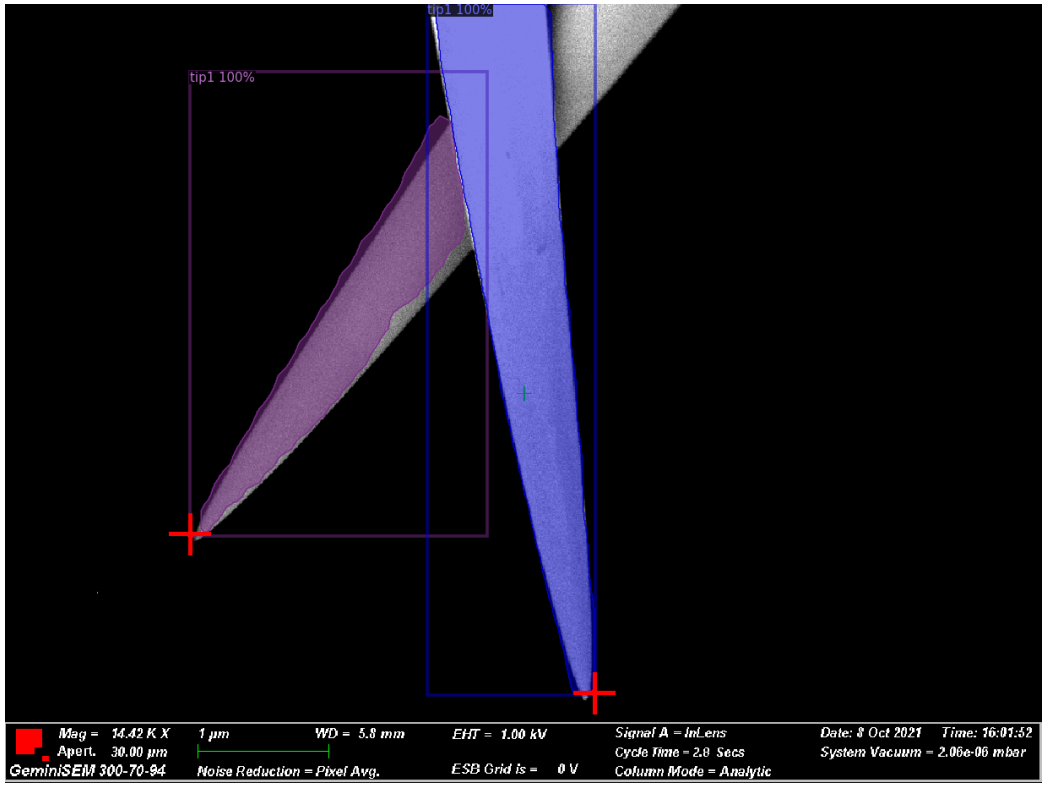


R101-DC5

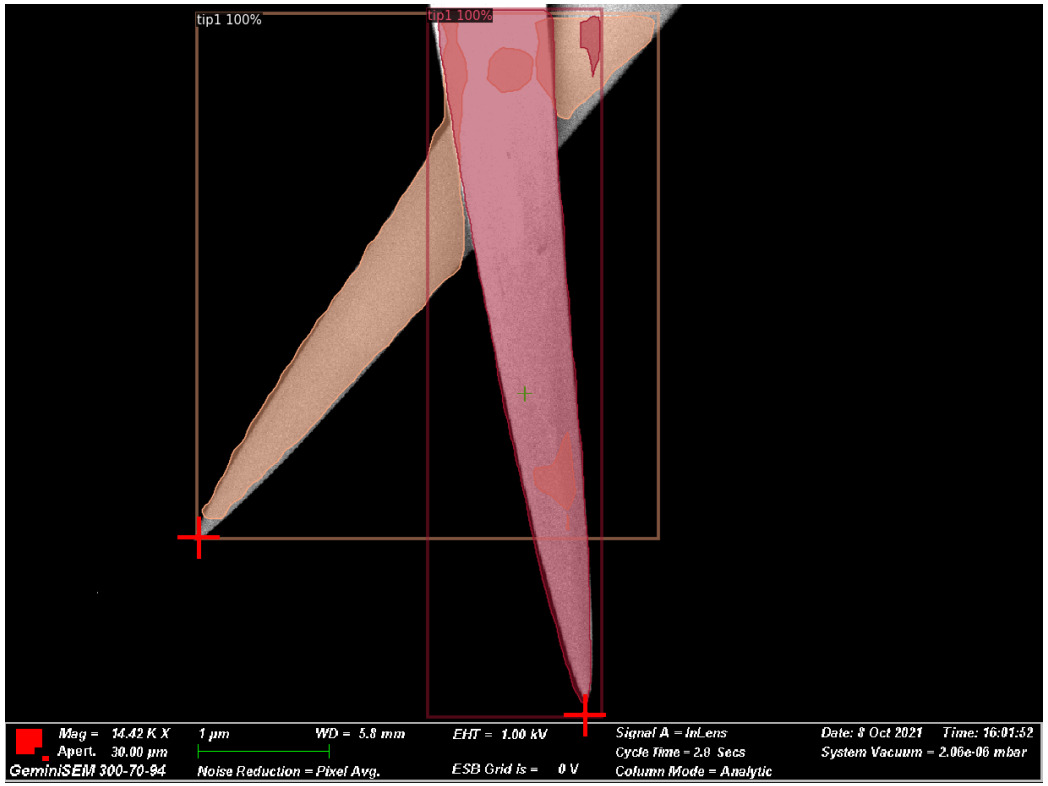


Tip Cleaning

R50-DC5

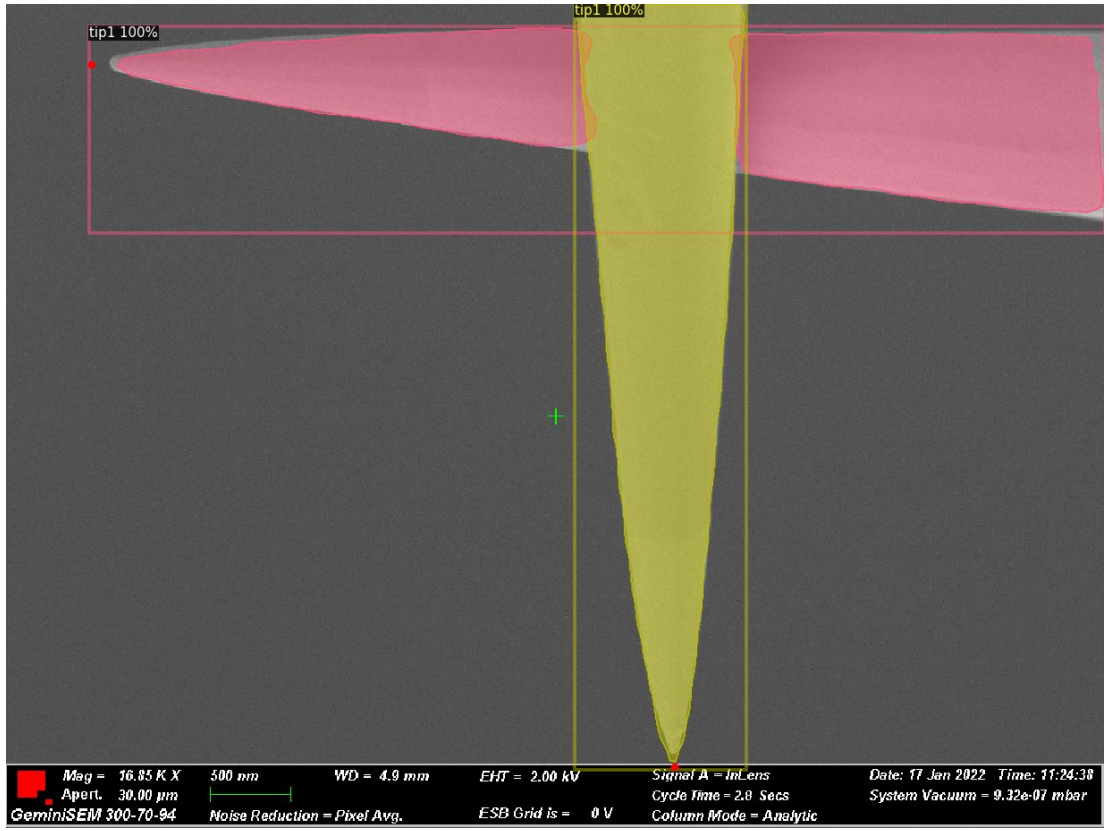


R101-DC5

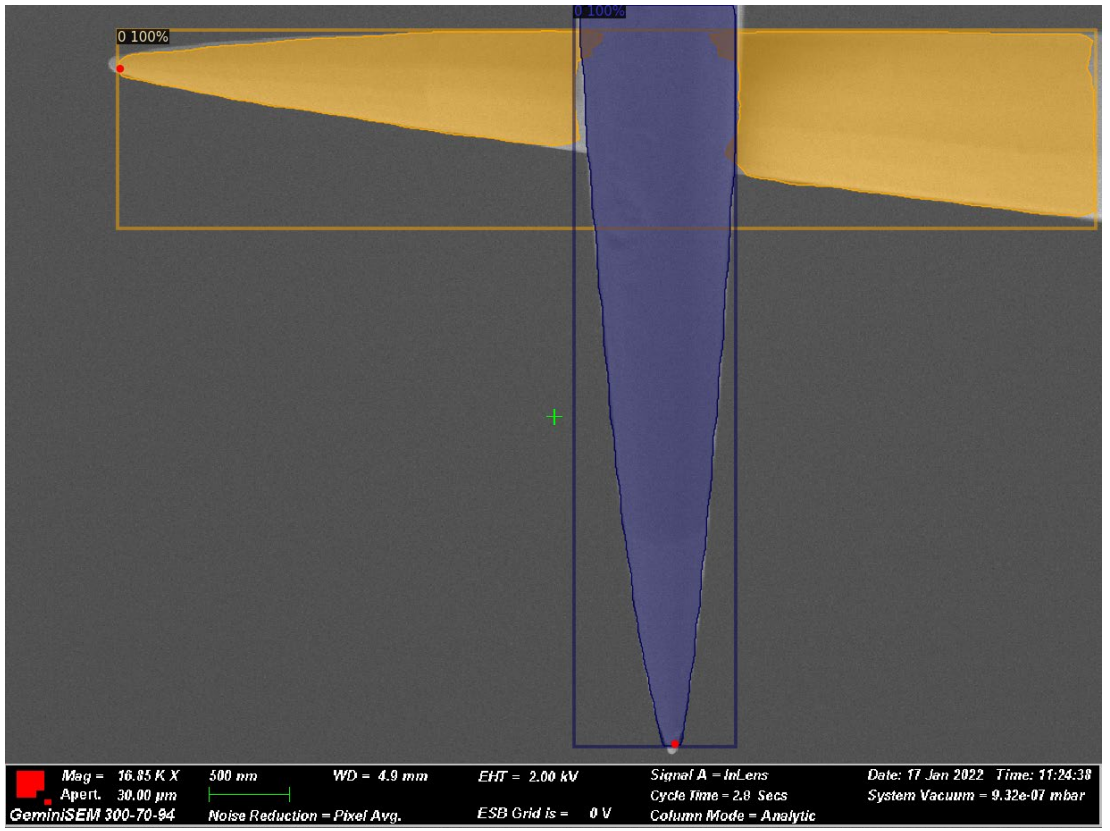


Tip Cleaning

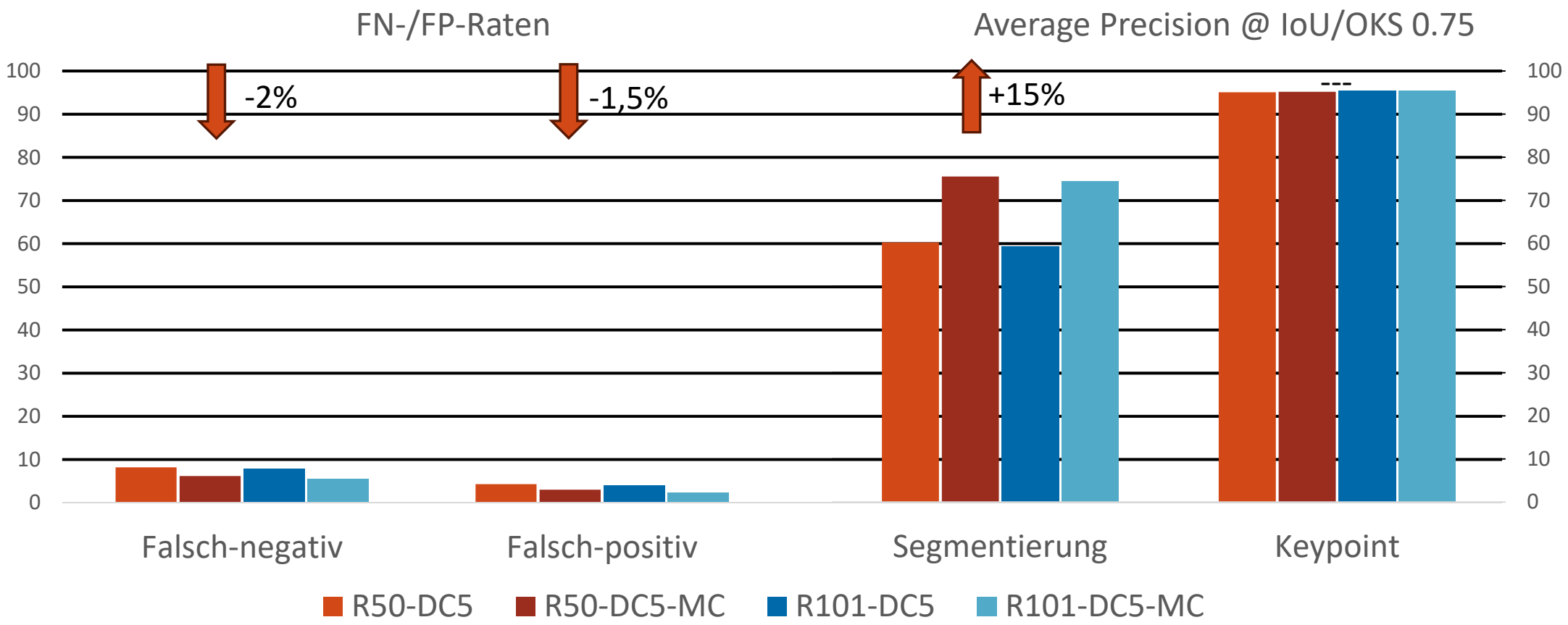
R50-DC5

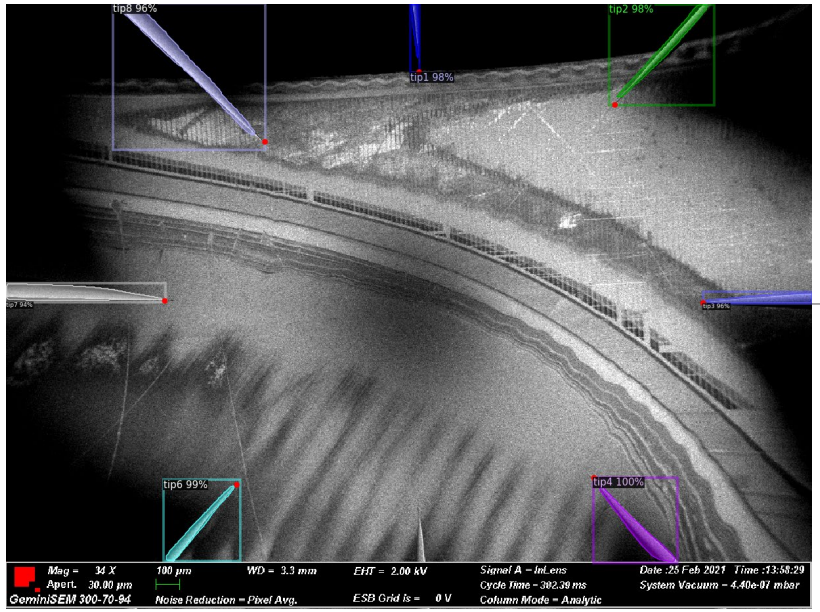


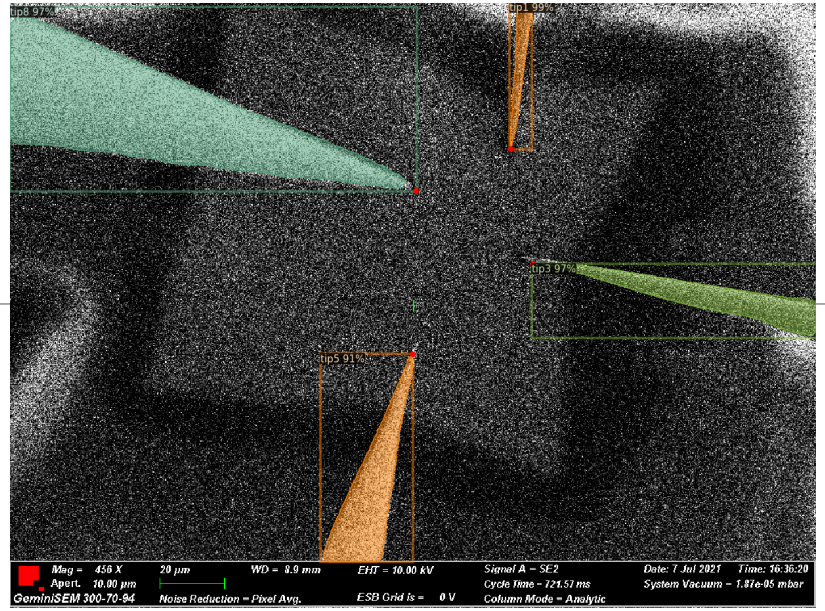
R101-DC5

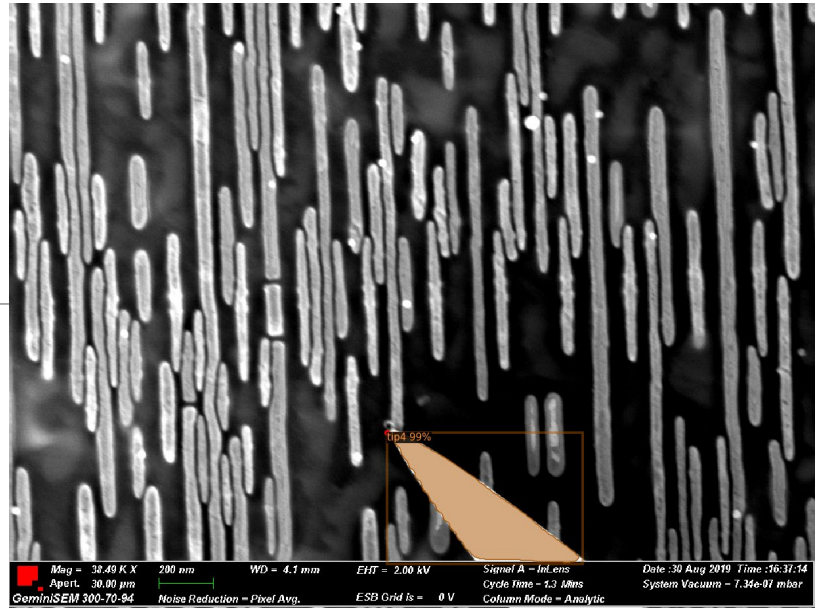


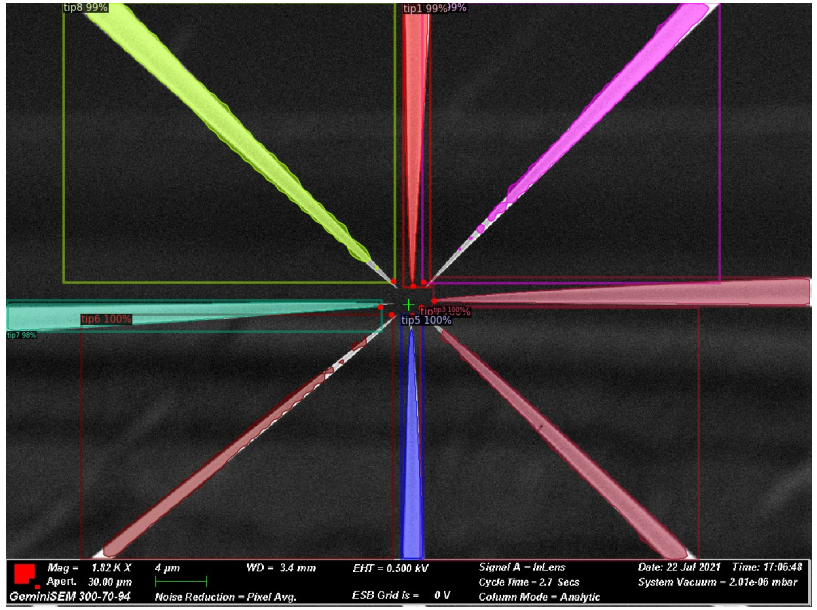
Multi Class Modelle

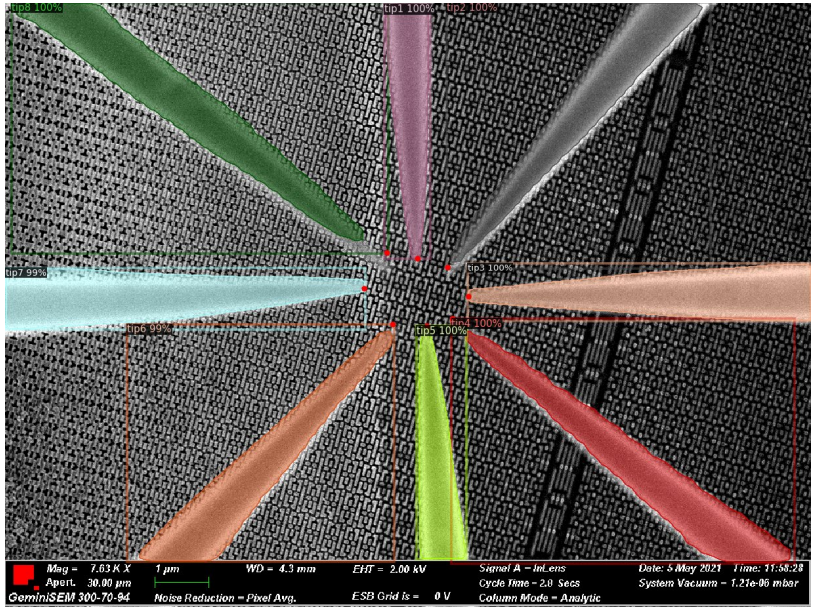


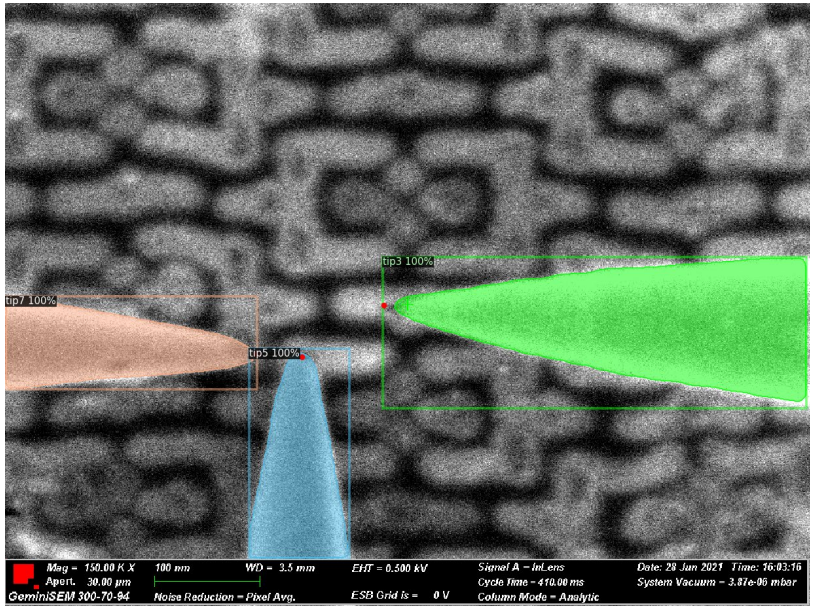

tip8 96%
tip2 98%
tip1 98%
tip6 99%
tip4 100%
Mag = 34 X
Apert. 30.00 µm
100 µm
WD = 3.3 mm
EHT = 2.00 kV
Signal A = InLens
Cycle Time = 302.39 ms
Date :25 Feb 2021 Time :13:58:29
System Vacuum = 4.40e-07 mbar
GeminiSEM 300-70-94
Noise Reduction = Pixel Avg.
ESB Grid is = 0 V
Column Mode = Analytic


tip8 97%
tip1 99%
tip3 97%
tip5 91%
Mag = 456 X
Apert. 10.00 µm
20 µm
WD = 8.9 mm
EHT = 10.00 kV
Signal A = SE2
Cycle Time = 124.57 ms
Date: 7 Jul 2021 Time: 16:36:20
System Vacuum = 1.81e-05 mbar
GeminiSEM 300-70-94
Noise Reduction = Pixel Avg.
ESB Grid is = 0 V
Column Mode = Analytic


tip4 99%
Mag = 38.49 K X
Apert. 30.00 µm
200 nm
WD = 4.1 mm
EHT = 2.00 kV
Signal A = InLens
Cycle Time = 1.3 Mins
Date :30 Aug 2019 Time :16:37:14
System Vacuum = 7.34e-07 mbar
GeminiSEM 300-70-94
Noise Reduction = Pixel Avg.
ESB Grid is = 0 V
Column Mode = Analytic


tip8 99%
tip1 99%
tip6 100%
tip5 100%
Mag = 1.82 K X
Apert. 30.00 µm
4 µm
WD = 3.4 mm
EHT = 0.500 kV
Signal A = InLens
Cycle Time = 2.7 Secs
Date: 22 Jul 2021 Time: 17:06:48
System Vacuum = 2.01e-06 mbar
GeminiSEM 300-70-94
Noise Reduction = Pixel Avg.
ESB Grid is = 0 V
Column Mode = Analytic


tip8 100%
tip1 100%
tip2 100%
tip7 99%
tip3 100%
tip6 99%
tip5 100%
tip4 100%
Mag = 7.63 K X
Apert. 30.00 µm
1 µm
WD = 4.3 mm
EHT = 2.00 kV
Signal A = InLens
Cycle Time = 2.0 Secs
Date: 6 May 2021 Time: 11:58:28
System Vacuum = 1.21e-06 mbar
GeminiSEM 300-70-94
Noise Reduction = Pixel Avg.
ESB Grid is = 0 V
Column Mode = Analytic


tip3 100%
tip7 100%
tip5 100%
Mag = 150.00 K X
Apert. 30.00 µm
100 nm
WD = 3.5 mm
EHT = 0.500 kV
Signal A = InLens
Cycle Time = 410.00 ms
Date: 28 Jun 2021 Time: 16:03:16
System Vacuum = 3.81e-06 mbar
GeminiSEM 300-70-94
Noise Reduction = Pixel Avg.
ESB Grid is = 0 V
Column Mode = Analytic

Fazit

- Deep Learning geeignet für Spitzenerkennung
- Resistent gegen Bildstörungen
- Zuverlässige Detektion
- Genaue Positionsbestimmung

→ Solide Grundlage

Ausblick

- Einsatzfähiges Modell

→ Grenzfälle Evaluieren

→ Datensatz Erweiterung

- Messspitzen Verfolgung

→ Ansteuerung beachten

- Integration in bestehende Software

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Danke für ihre Aufmerksamkeit!

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