Electronic Supplementary Information for:

Tunable Conduction Type of Solution-Processed Germanium Nanoparticle Based Field Effect Transistors and Their Inverter Integration

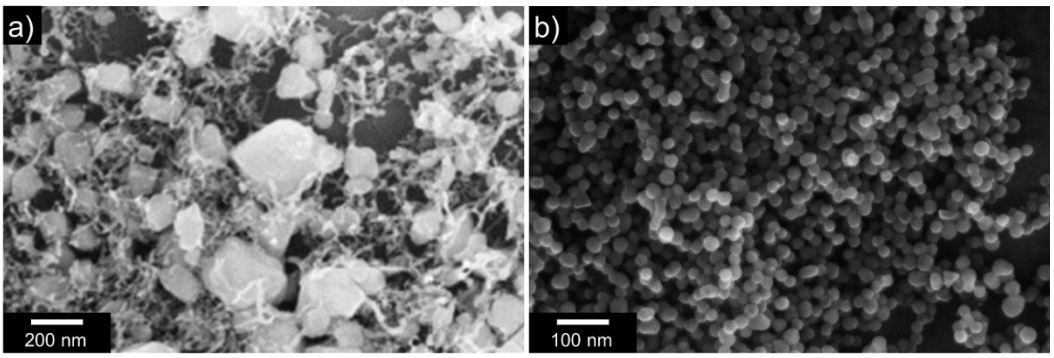
Zeynep Meric[†a] and Christian Mehringer[†b], Nicolas Karpstein[a], M. Jank[a,c], Wolfgang Peukert[b] and Lothar Frey [a,c]*

[a] Chair of Electron Devices, Friedrich-Alexander-Universität Erlangen-Nürnberg, Cauerstrasse 6, 91058 Erlangen, Germany

[b] Institute of Particle Technology, Friedrich-Alexander-Universität Erlangen-Nürnberg, Cauerstrasse 4, 91058 Erlangen, Germany

[c] Fraunhofer Institute for Integrated Systems and Device Technology, Schottkystrasse 10, 91058 Erlangen, Germany

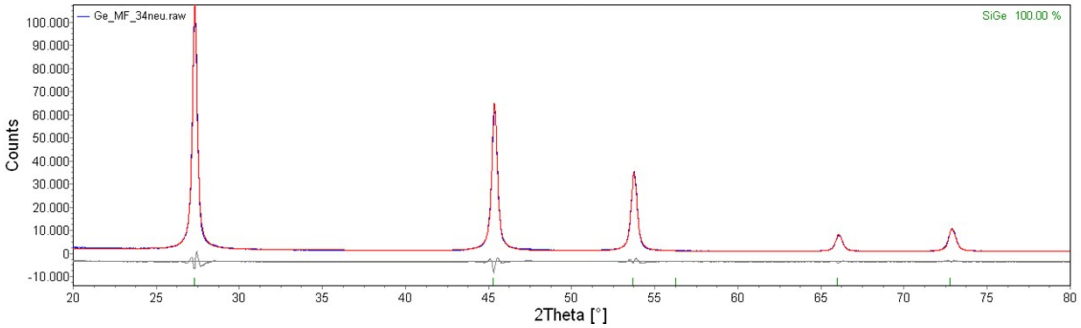
[†]These authors contributed equally



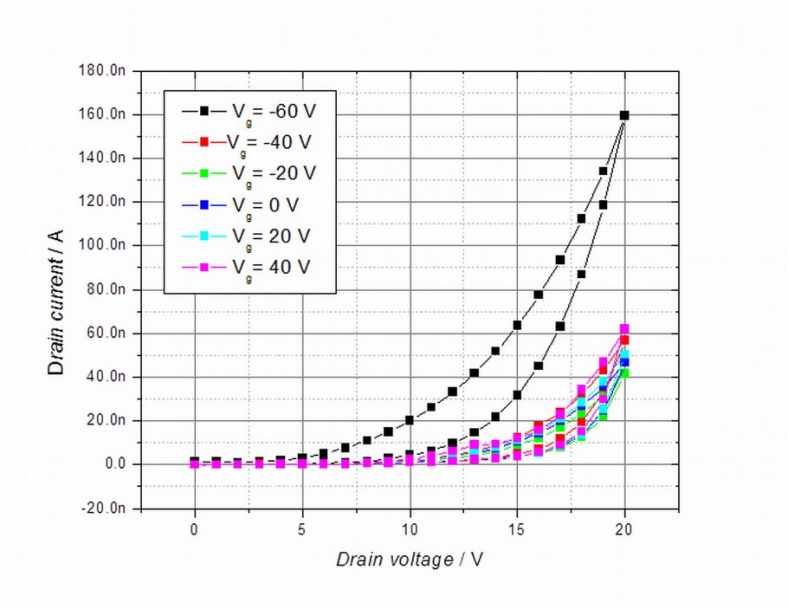
Suppl.Figure 1: Morphological effect of seeding. Same process conditions a) without and b) with seeding (exemplary shown: 700 °C; 0.5 mbar GeH_4 partial pressure in Ar).

Analysis report Ge NP powder

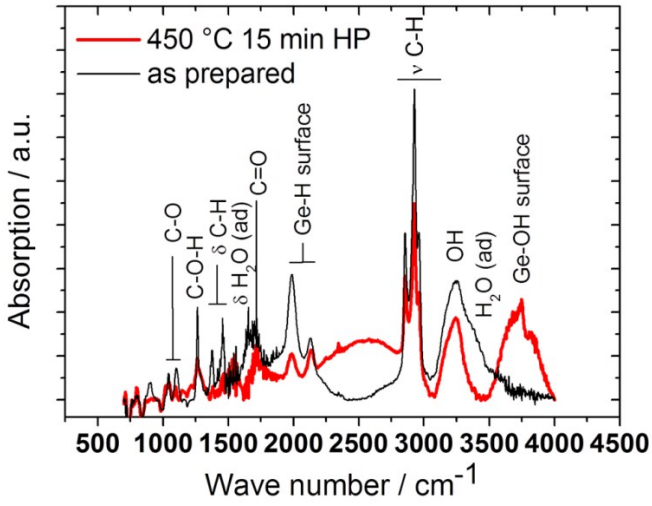
Structure 1		**Crystal Density (g/cm^3)**	**5.347**
Phase name	**SiGe**	**PV_TCHZ peak type**	
R-Bragg	**0.780**	**U**	**0.01**
Spacegroup	**Fd-3mS**	**V**	**0.01**
Scale	**0.0087952291**	**W**	**0.01**
Cell Mass	**583.710**	**Z**	**0**
Cell Volume (Å^3)	**181.27818**	**X**	**0.01**
Wt% - Rietveld	**100.000**	**Y**	**0**
Crystallite Size		**Lattice parameters**	
Cry Size Lorentzian (nm)	**37.2**	**a (Å)**	**5.6595493**
k: 1 LVol-IB (nm)	**23.693**		
k: 0.89 LVol-FWHM (nm)	**33.123**	**Site Np x y z Atom Occ Beq**	
Crystal Linear Absorption Coeff. (1/cm)	**364.280**	**Ge1 8 0.00000 0.00000 0.00000 Ge 1.008 1**	
		Si1 8 0.00000 0.00000 0.00000 Si -0.0079	



Suppl. Figure 2: Ge NP powder diffractogram (blue) with fit described above (red)

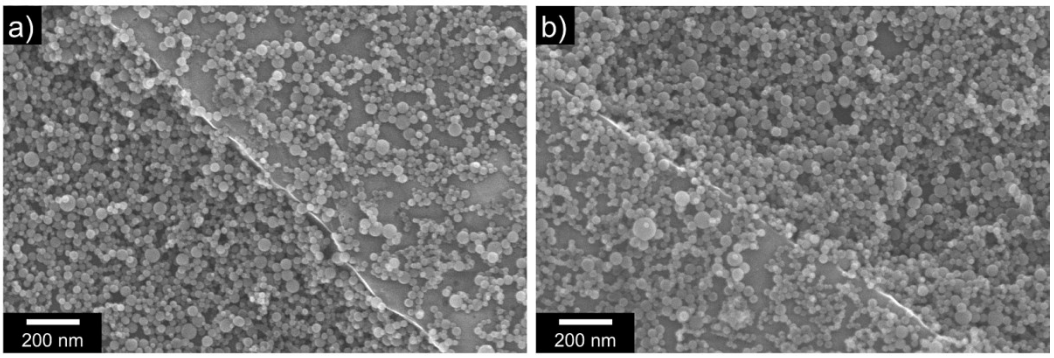


Suppl. Figure 3. The output characteristics of as deposited optimum (1 wt%; 3 deposition steps) layer shows low conductivity levels with minimal gating.

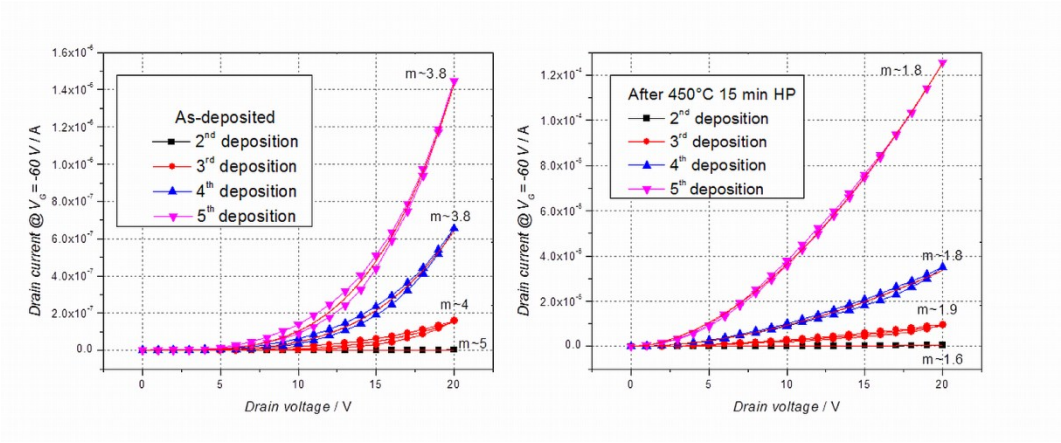


Suppl. Figure 4. Comparison of the FTIR spectra of an as prepared layer and a HP annealed layer (450 °C, 15 min). As the original layers are too thin to deliver spectra with evaluable intensities, very thick layers drop casted from 1 wt% dispersion are utilized. They are sealed under nitrogen in a protective cell equipped with a potassium bromide window. The intensity reduction of the C-O bands at 1042 and 1105 cm^{-1}, the C-O-H band at 1263 cm^{-1}, the δ C-H bands at 1376 and 1456 cm^{-1} as well as the ν C-H bands between 2800 and 3000 cm^{-1} shows a removal of solvent during hot plate annealing. However, the removal is not complete and cannot be quantified. Adsorbed water is also removed as can be seen at 1653 cm^{-1} and at the shoulder at ~ 3400 cm^{-1}.

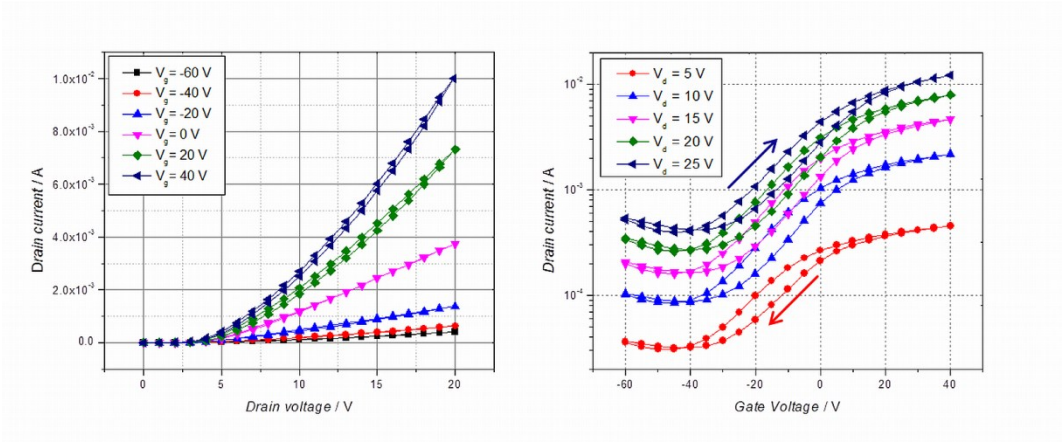
OH-groups (~ 3200 cm^{-1}) are present before and even after annealing and most likely belong to the solvent residues. Most importantly, the surface termination changes from mostly hydrogen-terminated in the as prepared layer (Ge-H at 1991 cm^{-1}) to mostly hydroxyl-terminated in the annealed layer (Ge-OH at ~ 3700 cm^{-1}).[1–4]



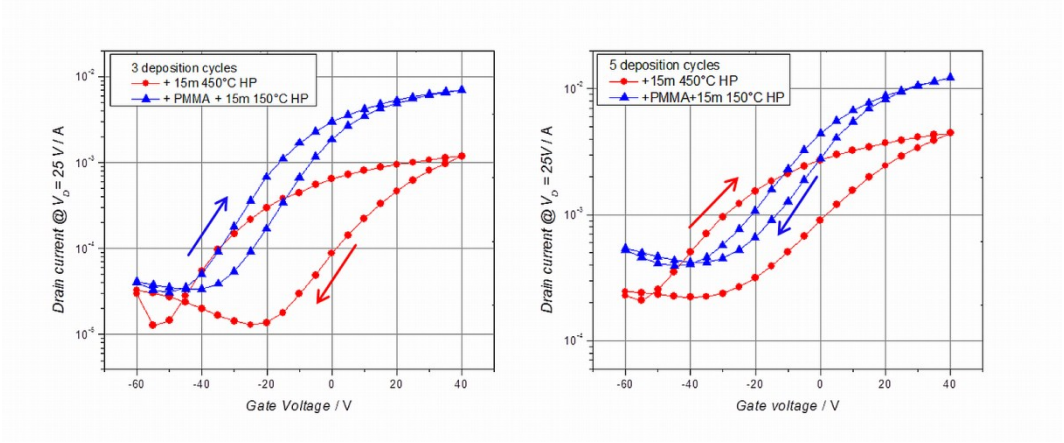
Suppl. Figure 5. Representative SEM images of a) as-prepared and b) HP annealed (450 °C, 15 min) layer on pre-structured substrate.



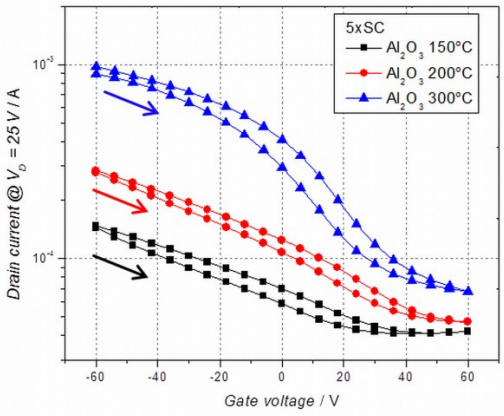
Suppl. Figure 6. The as-deposited GeNP layers investigated in this study show m values between 3.8 and 5 which determined from the slope of output curves. This proves that device characteristics obey the power-law $I \sim V^m$ with high m values observed for space-charge-limited-currents (SCLC). After annealing m values are well below 2 which indicates less trap density in the layer.



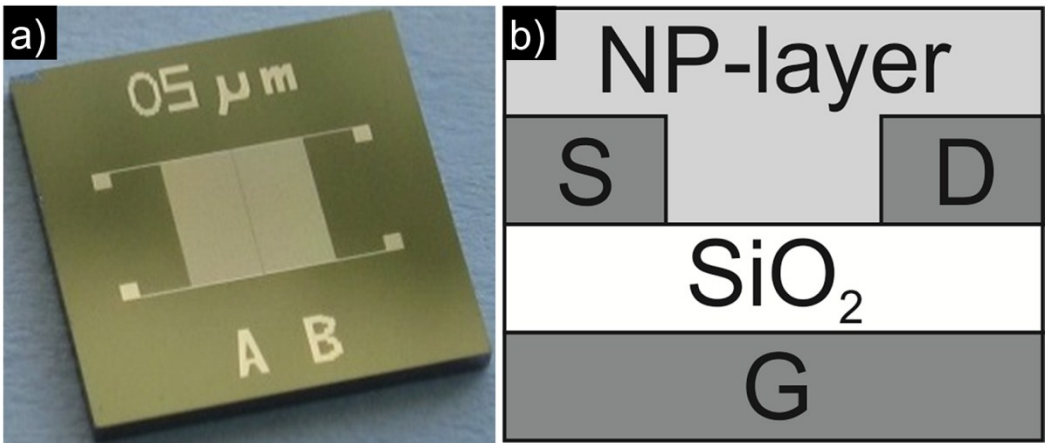
Suppl. Figure 7. The output and transfer characteristics of 5 times deposited (highest PAF value) sample after PMMA encapsulation.



Suppl. Figure 8. The comparison of 3 times and 5 times deposited layers improvements. Although 5 times deposited layer has highest particle coverage on the substrate, best electrical behavior can be seen for 3 times deposited layers (optimum).



Suppl. Figure 9. The transfer characteristics of 5 times deposited sample after ALD.



Suppl. Figure 10. a) Photography and b) schematic of the utilized pre-structured substrates showing source (S), drain (D) and gate (G).

REFERENCES

(1) Chou, Y.-P.; Lee, S.-C. *J. Appl. Phys*. 1998, *83* (8), 4111.
(2) Buriak, J. M. *Chem. Rev*. 2002, *102* (5), 1271–1308.
(3) Shirahata, N.; Hirakawa, D.; Masuda, Y.; Sakka, Y. *Langmuir*. 2013, *29* (24), 7401–7410.
(4) Raichlin, Y.; Millo, A.; Katzir, A. *Phys. Rev. Lett*. 2004, *93* (18).