TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

Faculty of Electrical Engineering and Information Technology, Semiconductor and Microsystems Technology Laboratory

Vertical Graphene-Based Transistors for Power Electronics, Optoelectronics and Radio-Frequency Applications

TU-Dresden/ IHM (Institute of Semiconductors and Microsystems, Chair for Nanoelectronics)

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FFLexCom

High Frequency Flexible Bendable Electronics
for Wireless Communication Systems

DFG PRIORITY PROGRAMME (SCHWERPUNKTPROGRAMM) 1796

TECHNISCHE UNIVERSITÄT DRESDEN

IHM

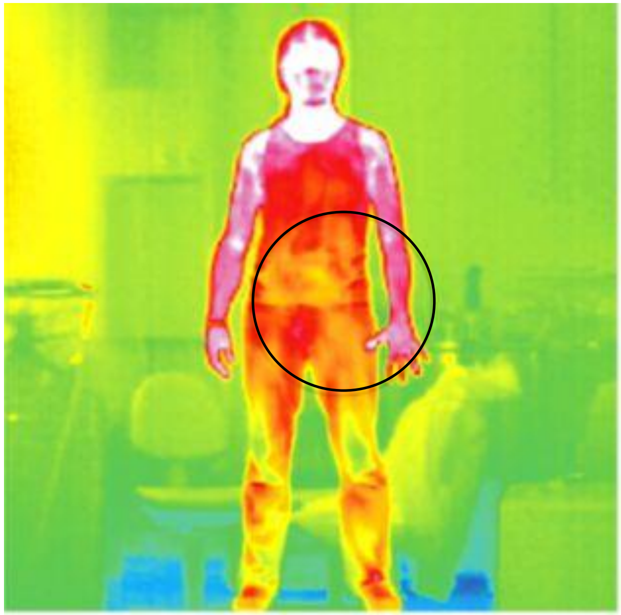
Dresden, 09/2023

Agenda

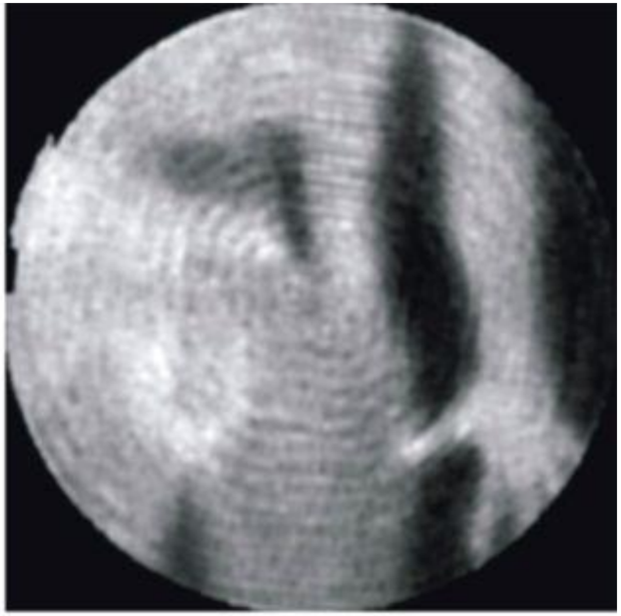
1 Hot electron transistor (HET)

Terahertz gap: 0.1 – 10 THz, technology for its **generation** and **manipulation** is still in its **infancy**

⇨ but several **applications:** communications, imaging, spectroscopy and security



infrared camera



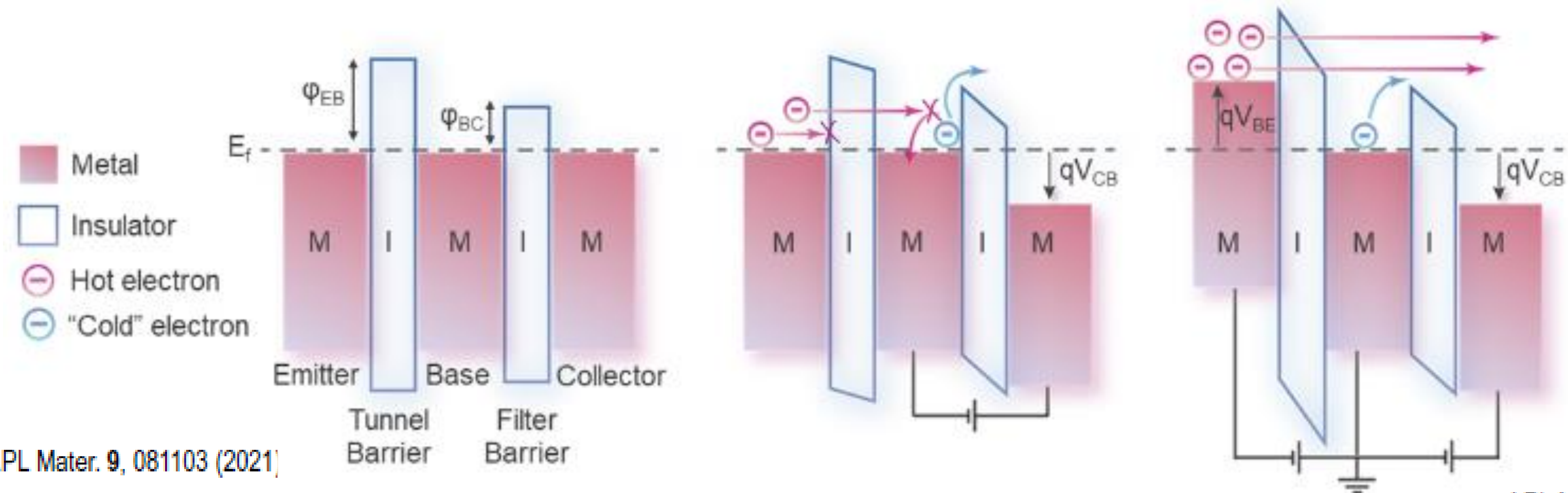
THz camera

- e.g. clothing transparent for THz radiation
- no ionizing or damaging effect of THz radiation on biological materials

⇨ high **demand** for novel **THz devices**, i.e. transistors

1 Hot electron transistor (HET)

Hot electron transistor (HET) first proposed in 1960 with a MIMIM structure



APL Mater. 9, 081103 (2021)

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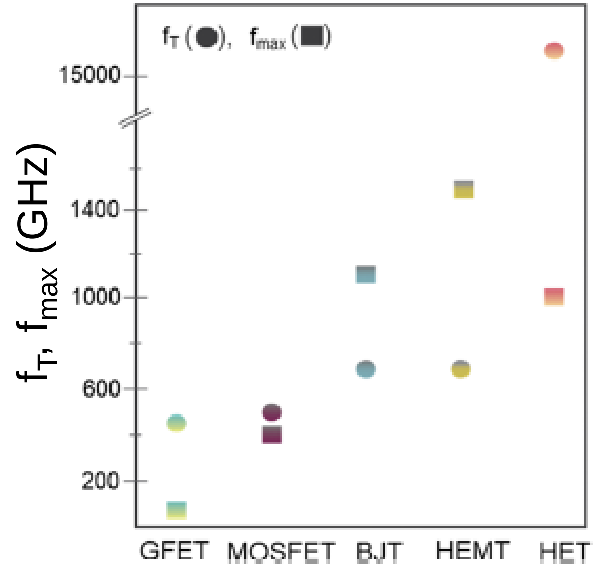
- Electrons injected from the emitter into the metal base have a higher energy (**hot electrons**) compared to the Fermi energy of the base electrons (**cold electrons**).
- **metal base thickness** could not be scaled down sufficiently (scattering)

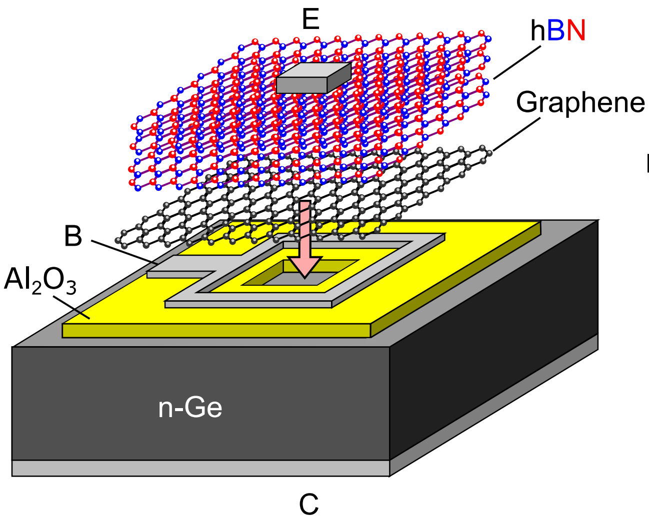
→ 2D materials (Graphene)

→ ultra-short base transit times

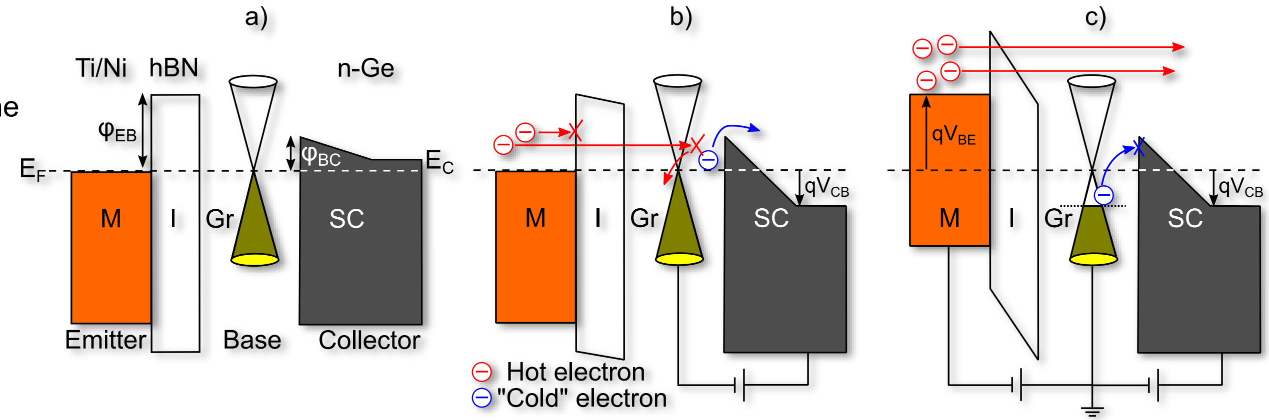
→ superior high-frequency performance predicted



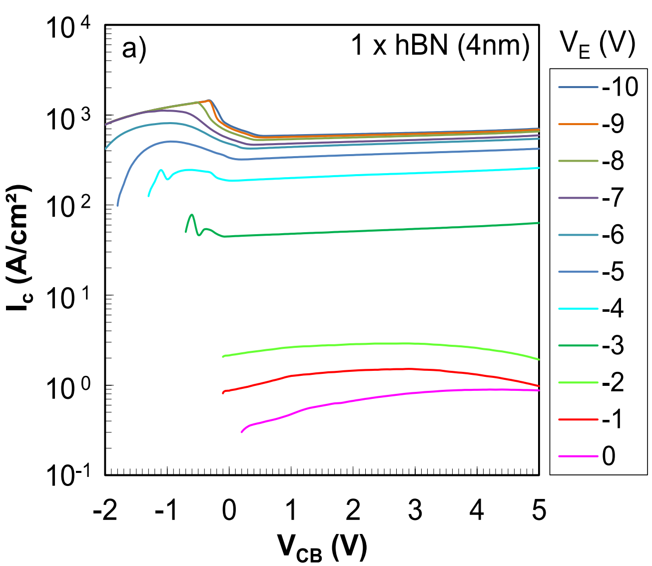
1 Hot electron transistor (HET)

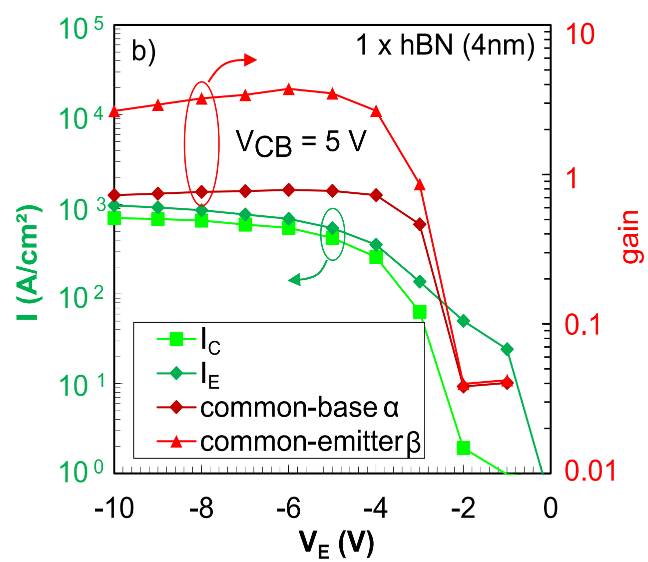


novel **HET** design with **graphene (Gr) base**



C. Strobel et al., **High Gain Graphene Based Hot Electron Transistor with Record High Saturated Output Current Density**, Advanced Electronic Materials, to be published





1 Hot electron transistor (HET)

No.	Year	Structure				J_C	α_{max}	Limitations	Ref.
		E	Barrier 1	B	Barrier 2	(A/cm^2)			
1	2013	n-Si++	SiO_2	Gr	HfO_2	9×10^{-8}	0.048	low α_{max}, low J_C	8
2	2013	n-Si+	SiO_2	Gr	Al_2O_3	2×10^{-5}	0.065	low α_{max}, no current saturation	7
3	2015	n-Si++	SiO_2	MoS_2	HfO_2	10^{-4}	0.95	low J_C, no current saturatio	19
4	2019	Al	$SrTiO_3$	$SrRuO_3$	$Nb{:}SrTiO_3$	1	0.35	low α_{max}	21
5	2019	GaN	AlGaN	Gr	Al_2O_3	1	0.15	low α_{max}	22
6	2015	n-Si+	$TmSiO/TiO_2$	Gr	Si	3	0.2	low α_{max}	18
7	2023	Ti	n-a-Si:H	Gr	n-Si	3	0.02	low α_{max}	20
8	2017	GaN	AlN	Gr	WSe_2	50	0.75	no current saturation	23
9	2019	Gr	hBN (10nm)	Gr	WSe_2	400	0.99	low V_{CB} window	14
this work		**Ti**	**hBN (4nm)**	**Gr**	**n-Ge**	**800**	**0.87**		

7. Vaziri, S. *et al.* A Graphene-Based Hot Electron Transistor. *Nano Lett.* **13**, 1435–1439 (2013).

8. Zeng, C. *et al.* Vertical Graphene-Base Hot-Electron Transistor. *Nano Lett.* **13**, 2370–2375 (2013).

19. Torres, C. M. Jr. *et al.* High-Current Gain Two-Dimensional MoS2-Base Hot-Electron Transistors. *Nano Lett.* **15**, 7905–7912 (2015).

21. Kim, B. S. Y., Hikita, Y., Yajima, T. & Hwang, H. Y. Heteroepitaxial vertical perovskite hot-electron transistors down to the monolayer limit. *Nat. Commun.* **10**, 5312 (2019).

22. Giannazzo, F. *et al.* High-Performance Graphene/AlGaN/GaN Schottky Junctions for Hot Electron Transistors. *ACS Appl. Electron. Mater.* **1**, 2342–2354 (2019).

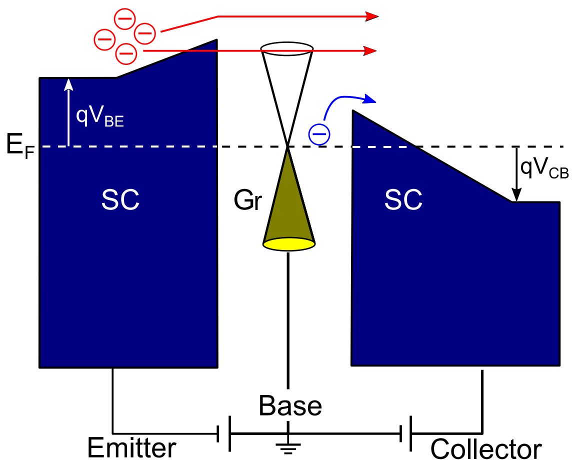
18. Vaziri, S. *et al.* Bilayer insulator tunnel barriers for graphene-based vertical hot-electron transistors. *Nanoscale* **7**, 13096–13104 (2015).

20. Strobel, C. *et al.* Enhanced Electrical Properties of Optimized Vertical Graphene-Base Hot Electron Transistors. *ACS Appl. Electron. Mater.* (2023).

23. Zubair, A. *et al.* Hot Electron Transistor with van der Waals Base-Collector Heterojunction and High-Performance GaN Emitter. *Nano Lett.* **17**, 3089–3096 (2017).

14. Liu, W. *et al.* Approaching the Collection Limit in Hot Electron Transistors with Ambipolar Hot Carrier Transport. *ACS Nano* **13**, 14191–14197 (2019).

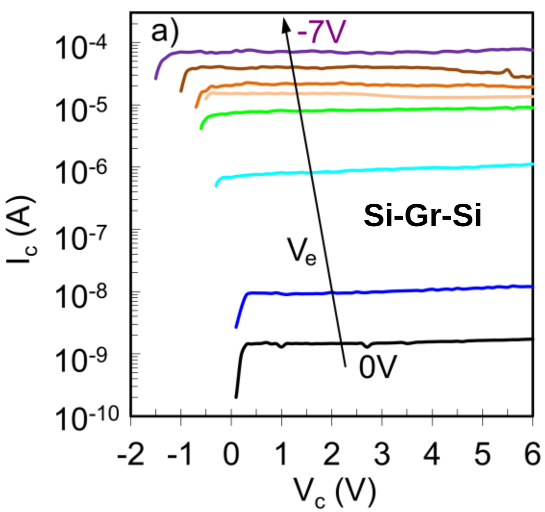
simplest HET design: semiconductor-graphene-semiconductor (SGS)

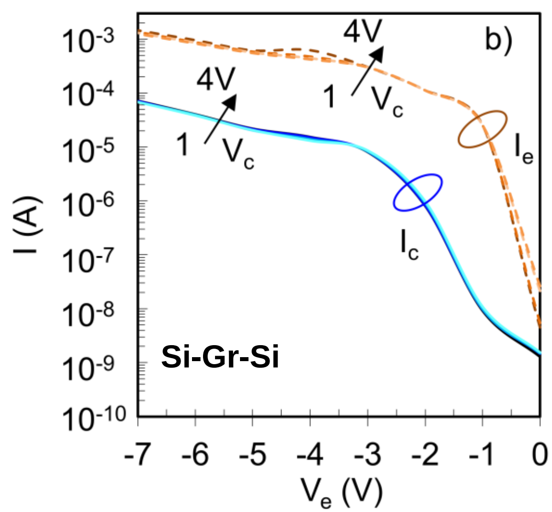


Si-Gr-Si ⟶ $\alpha \approx 0.02$

- first Si on graphene deposition without damaging graphene (VHF-PECVD)

G. Lupina, C. Strobel, J. Dabrowski, et al., **Plasma-enhanced chemical vapor deposition of amorphous Si on graphene**, **Appl. Phys. Lett., vol. 108, no. 19, p. 193105, (2016)**



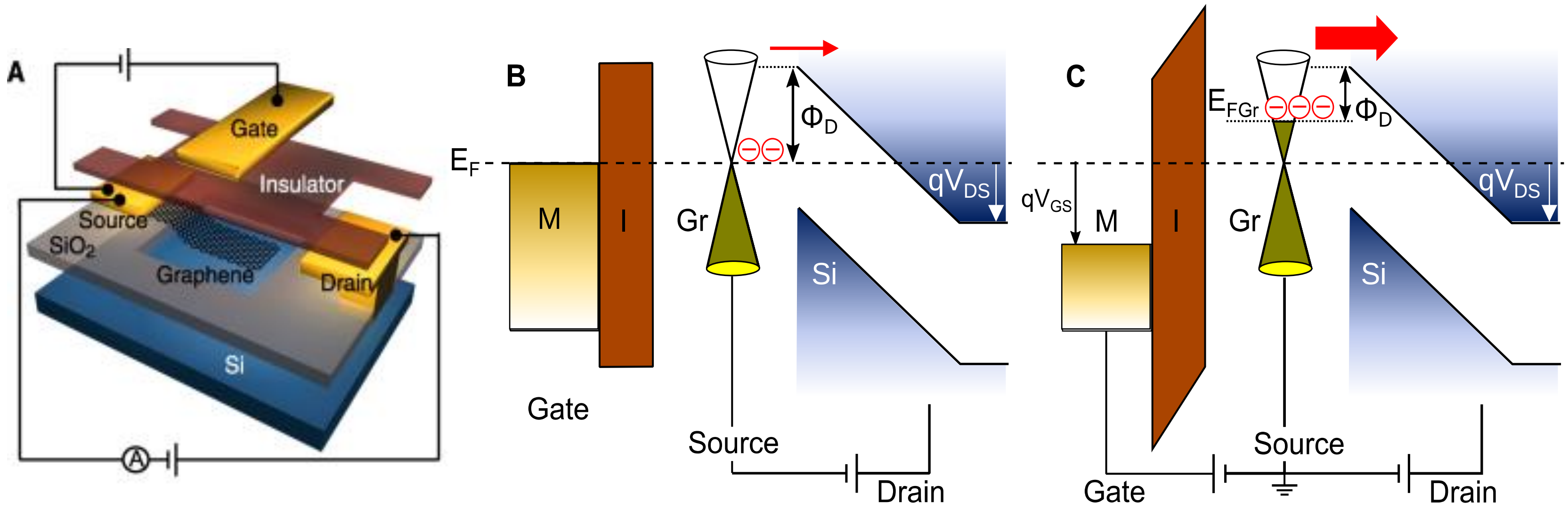


- on-off > 1x10^5 (larger than predicted theoretically)

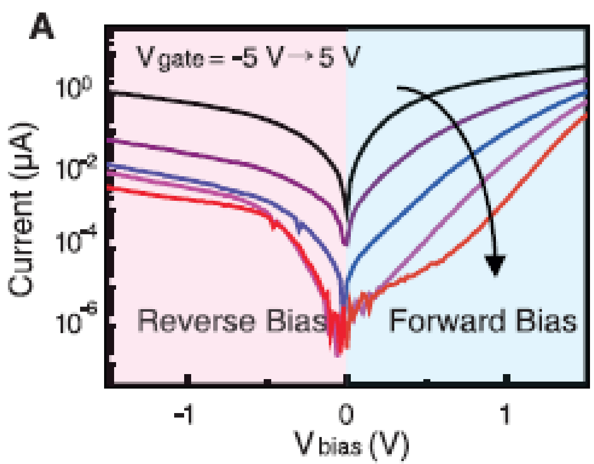
C. Strobel et al., **Enhanced Electrical Properties of Optimized Vertical Graphene-Base Hot Electron Transistors**, **ACS Applied Electronic Materials 5 (3), 1670-1675 (2023)**

Agenda

2 Barristor



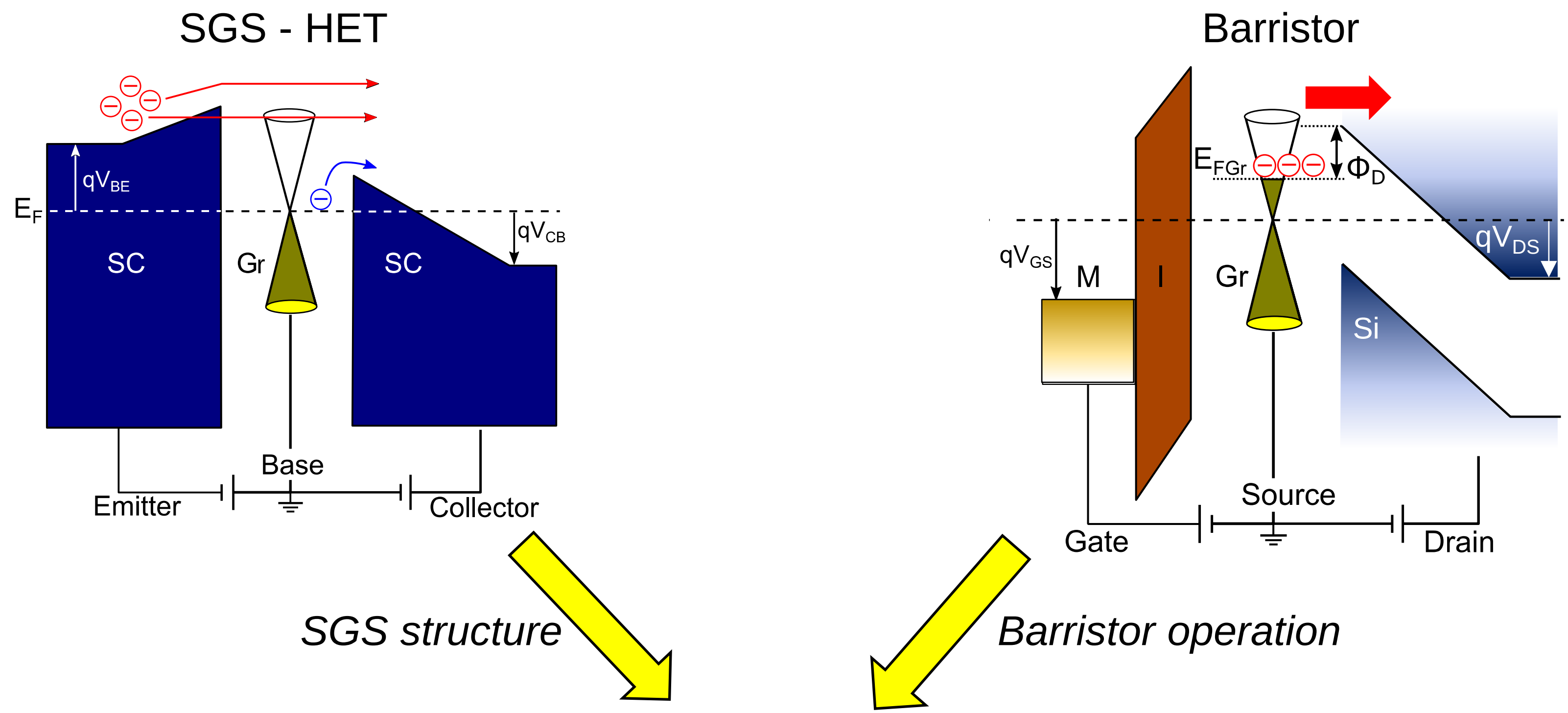
H. Yang, SCIENCE, Vol 336, Issue 6085, pp. 1140-1143 (2012)

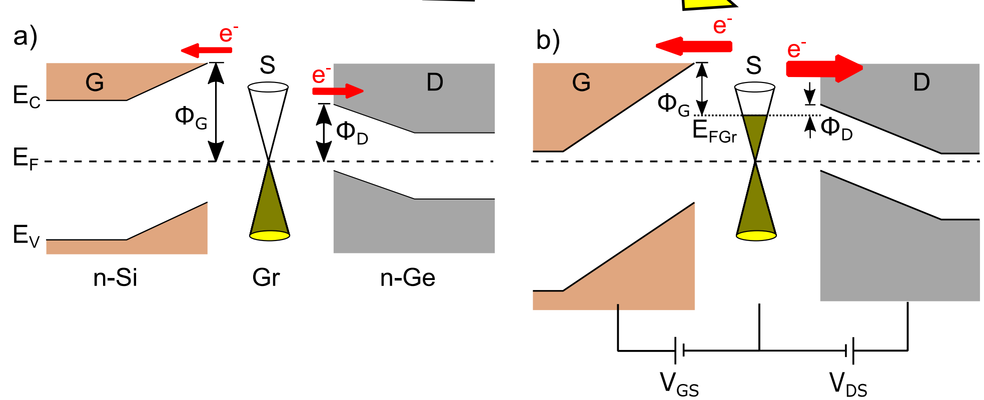


- Barristor **overcomes** the weak **on/off** ratio of lateral graphene field-effect transistors (**GFET**)
- **gate voltage** controls the **Gr-Si Schottky barrier** Φ_D, and thus the drain current
- **ON-OFF ≈ 10^7** achieved (suitable for switching applications)
- high on-current up to 10^4 A/cm² demonstrated

Agenda

3 Graphene adjustable barriers transistor (GABT)



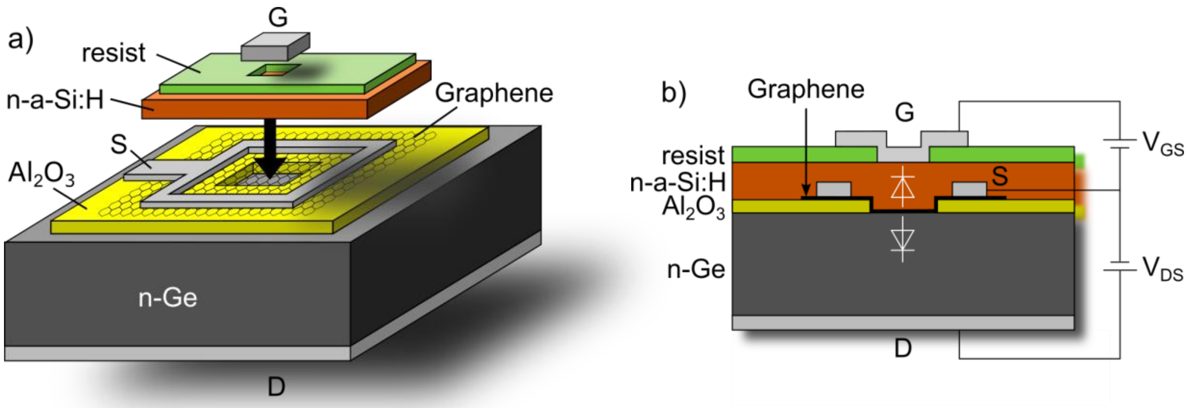


Graphene adjustable barriers transistor (GABT)

Strobel, C. *et al.*
Novel Graphene Adjustable-Barrier Transistor with Ultra-High Current Gain.
***ACS Appl. Mater. Interfaces* 14, 39249–39254 (2022).**

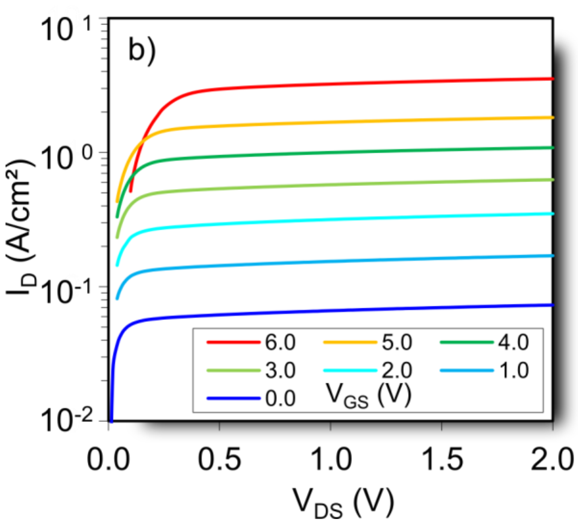
C. Strobel, *DPMA P83689*, vol. **Patent 10 2022 106 012.8 DE**, Mar. 2022.

3 Graphene adjustable barriers transistor (GABT)

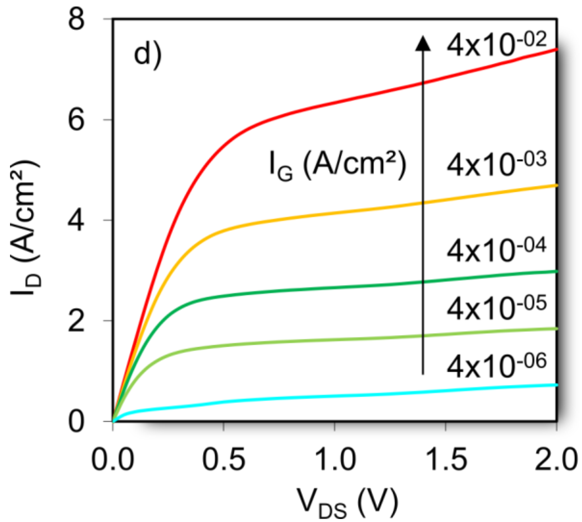


- device performance strongly depends on **semiconductor gate thickness**
- device modelling predicts strongly improved performance when gate thickness **< 5nm (2D materials)**

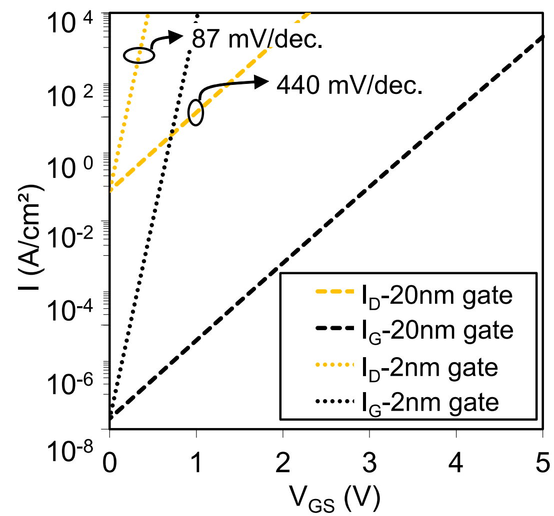
- GABT device research still in its infancy



on-off < 10^2

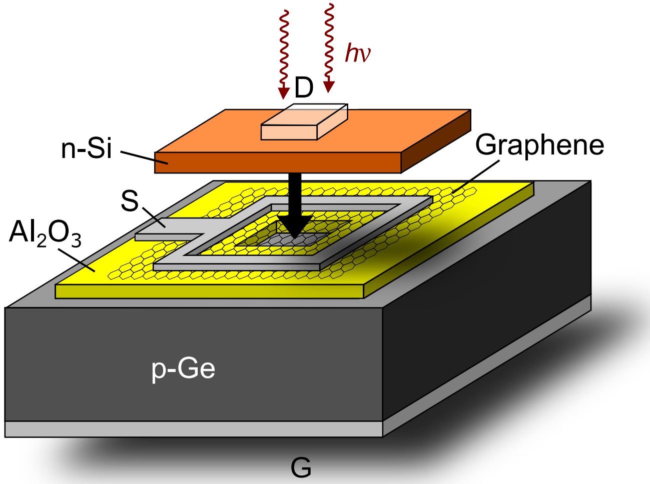


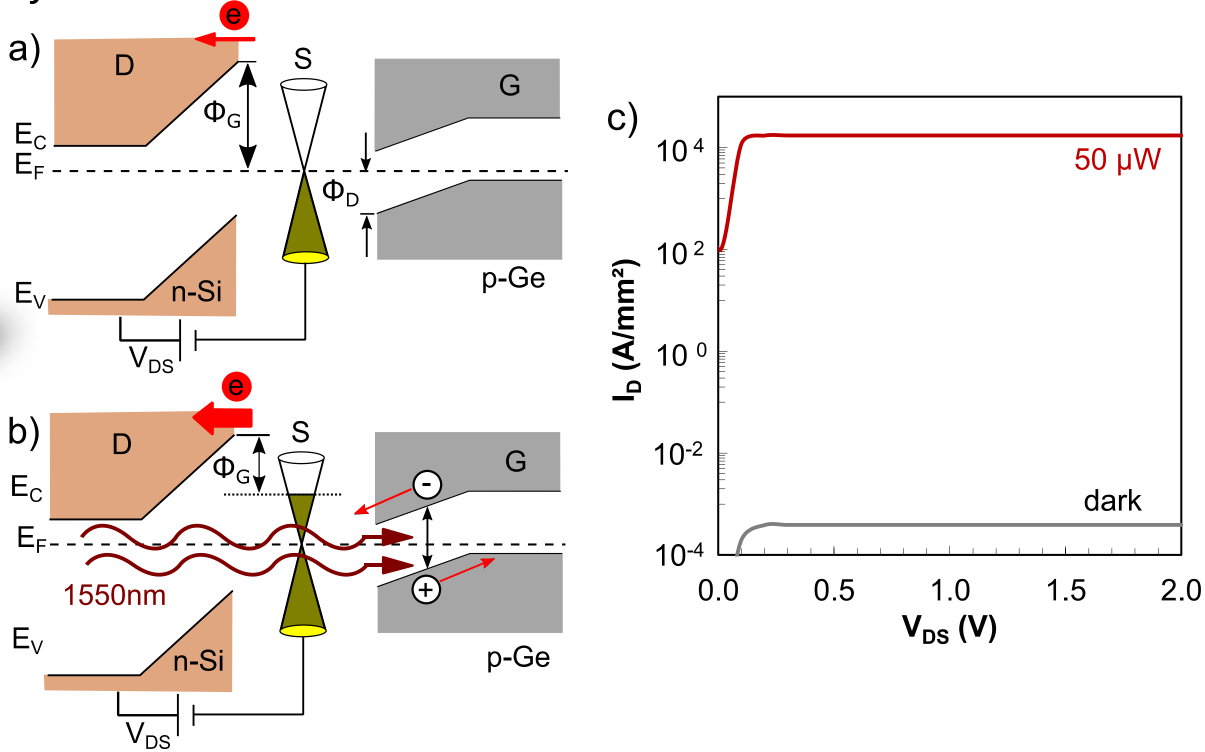
current gain $I_D/I_G \approx 10^6$
(V_{GS} = 1V)



3.1 GABT phototransistor

- **high speed** photodetectors required in **fiber optic** communication systems **(1550nm)**
- so far **photodiodes** (f_{cmax} ≈ 265 GHz) + external **transimpedance amplifiers**
- phototransistors too slow today





C. Strobel, *DPMA P87474*, vol. **Patent 10 2023 113 982.7 DE**, Mai. 2023.

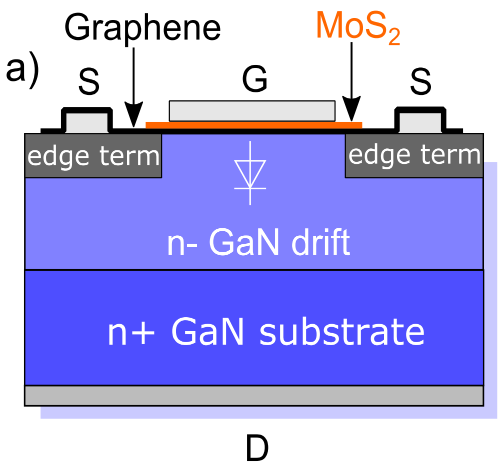
calculations: ⇨ photo gain 2.5 x 10^8 (responsivity 2.8 x 10^8 AW^{-1})

transit time -> f_c ≈ 100 GHz
RC delay -> f_c ≈ 3 GHz

⇨ unique performance combination

3.2 GaN-GABT

- GABT technology can also be applied as a power electronics switch



- area junction device -> **high currents** up to 10^6 A/cm² predicted
- **low device size**
- low on-state carrier density graphene 2.5 x 10^{12} cm^{-2}
- **ultra-low gate charge** ≈ 8pC (reference HEMT devices 1-10nC)
- **lower power dissipation**
- 10MHz GABT gate current = 80µA
- 10MHz HEMT gate current = 10-100mA
- **increased ESD robustness**
- lower capacities -> **faster switching transients**

Criterion	Si-IGBT	Si-MOSFET	HEMT	GaN-GABT
on-resistance	++	o	++	++
voltage blocking	+	-	o	+
gate charge	o	o	+	++
switching speed	-	+	++	++
ESD-robustness	o	o	o	+

(rating: ++ excellent + good o still acceptable - not sufficient)

Conclusions

- **Hot electron transistors** (HETs) promising for **Terahertz technology** with predicted f_T up to **15 THz**
- **Record Jc** and **current gain β > 1** achieved with M-I-Gr-SC HET design
- Simplest HET design „**semiconductor-graphene-semiconductor** (SGS)“ also widely investigated
- **Barristor** is another promising vertical graphene-based device for switching applications
- Merging the SGS HET structure with the Barristor operation principle leads to a new device termed „**Graphene Adjustable-Barriers Transistor (GABT)**“
- GABT technology especially promising for photonics and power electronics
- **photo-GABT** potentially offers unique performance parameters such as high responsivities (**> 1x** $\mathbf{10^8}$ **AW**$^{\mathbf{-1}}$) and high speed (**> 1 GHz**)
- **GaN-GABT** power switch with **ultra-low gate charge** and thus power dissipation seems feasible

Thank you for your attention!

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