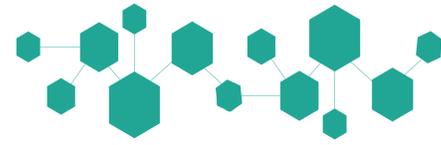




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# Graphene Industrial Forum & 2DM 2020



## Gate-tunable graphene-based Hall sensors on flexible substrates with increased sensitivity

Burkay Uzlu, Zhenxing Wang, Sebastian Lukas, Martin Otto, Max C. Lemme & Daniel Neumaier

### INTRODUCTION

#### Applications of Hall sensors

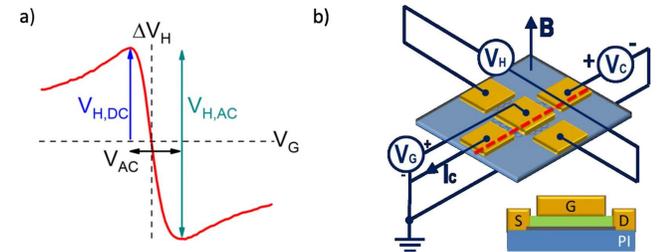
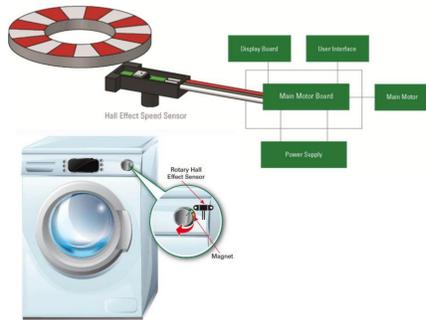
- Speed Detection
- Precise Rotation Detection

#### Application Fields of Hall sensors

- Automotive
- Consumer Electronics
- Telecommunication
- Medical

#### Key Parameters

- $S_v \sim \mu$ ,  $S_i \sim 1/n$  and  $B_{min}$
- Graphene is an ideal material Due to;
- High mobility
- Low carrier concentration

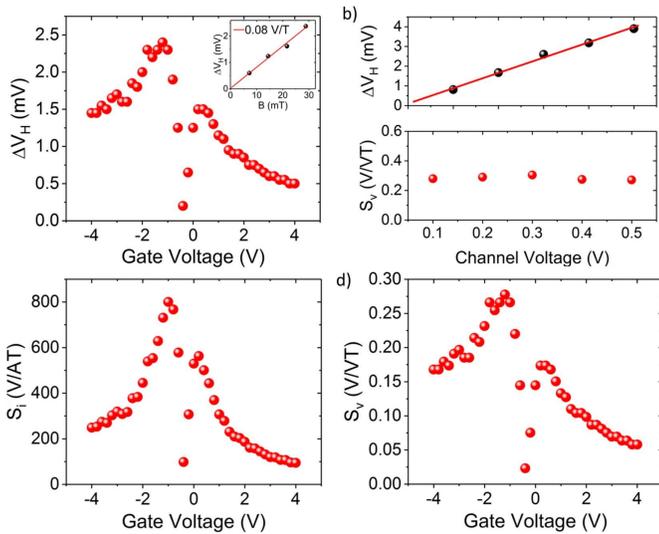


Alternating current (AC) modulated gate voltage provides two important advantages compared to Hall sensors under static operation;

1. The sensor sensitivity can be doubled by utilizing both n- and p-type conductance.
2. A static magnetic field can be read out at frequencies in the kHz range, where the  $1/f$  noise is lower compared to the static case. (better  $B_{min}$ )

- Flexibility opens up new application fields like wearable sensors for personal fitness and healthcare systems.

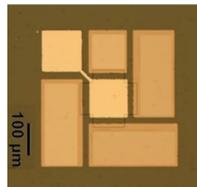
### Hall Sensor Under Static Operation



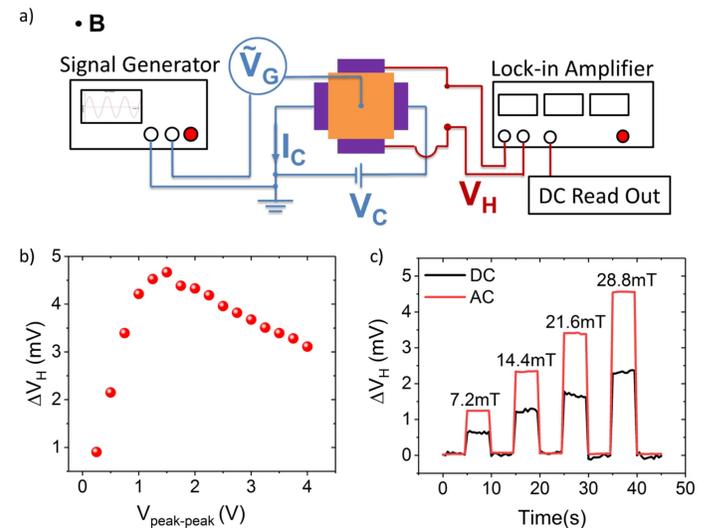
Hall measurements of the sensor. (a) Magnitude of the  $\Delta V_{Hall}$  as a function of the gate voltage at  $V_{channel} = 300$  mV. The inset shows  $\Delta V_{Hall}$  as a function of the magnetic field at  $V_{Gate} = -1.2$  V. (b)  $\Delta V_{Hall}$  and voltage sensitivity  $S_v$  as a function of channel voltage. (c,d) Absolute values of current sensitivity  $S_i$  and  $S_v$  plotted against  $V_{Gate}$  at  $V_{channel} = 300$  mV.

Measured Hall Mobility of the graphene is  $4400 \text{ cm}^2/\text{Vs}$

### Microscope Image



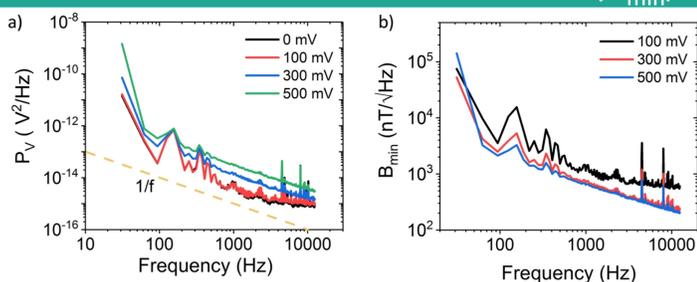
### Hall Sensor Under AC modulated Gate Voltage



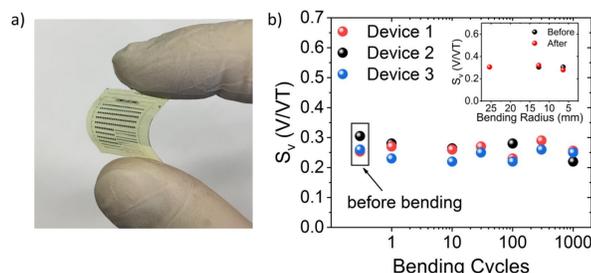
(a) Illustration of AC gate modulation setup. (b) Hall voltage response of the device to the varying magnetic field at a peak to peak gate modulation amplitude at 28.8 mT. (c) Offset removed Hall voltage under DC (black) and AC (red) operation over time, while the magnetic field was stepped between 7.2 mT up to 28.8 mT

- Sensitivity is doubled compared to static operation and values up to  $0.55 \text{ V/VT}$  was achieved on flexible polyimide (PI) substrates.

### Noise and Minimum detectable field ( $B_{min}$ )



### Bending Tests For Flexible Hall Sensor



### Comparison with Other Hall Elements

	Substrate	$S_i$ (V/AT)	$S_v$ (V/VT)	$B_{min}$ (nT/ $\sqrt{\text{Hz}}$ )	Frequency (kHz)	Conditions	
	Si <sup>1,28</sup>	Rigid	100	0.1	5000	3	n/a
	AlInSb <sup>4,6</sup>	Rigid	2750	2.2	58	1	Vacuum
	GaAs <sup>28</sup>	Rigid	1100	n/a	800	3	n/a
	Exfoliated Gr-hBN <sup>9</sup>	Rigid	4100	2.16	50	3	Vacuum
	CVD Gr <sup>29</sup>	Rigid	800	n/a	500	3	Vacuum
	CVD Gr <sup>10</sup>	Rigid	2093	0.35	100	3	Air
	CVD Gr <sup>8</sup>	Flexible	75	0.093	n/a	n/a	Air
	CVD Gr-hBN <sup>22</sup>	Flexible	2270	0.68	n/a	n/a	Air
	Bismuth <sup>31</sup>	Flexible	2.3	n/a	n/a	n/a	Air
	This work	Flexible	1500	0.55	500	2	Air
	This work (max)	Flexible	2580	0.68	290	2	Air

Metrics comparison of different high-performance Hall elements working at room temperature

- Results show that our CVD graphene based Hall sensors on flexible substrates outperforms all the other Hall sensor elements on flexible substrates and are highly competitive with respect to all existing technologies on rigid substrate. The measured minimum magnetic resolution of our Hall sensors also is close to the very best values achieved by exfoliated graphene based Hall sensors

### CONTACT PERSON

Burkay Uzlu  
uzlu@amo.de

### ACKNOWLEDGEMENTS



### REFERENCES

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