

# Metal as classical gas: Drude model



resistivity measurements



thermoelectrics

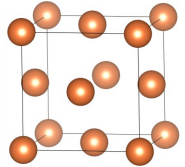


Paul Drude



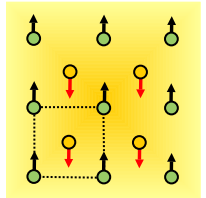
## 1. Structure of crystals

- direct lattice / reciprocal lattice
- symmetry
- crystal structure / structure factor



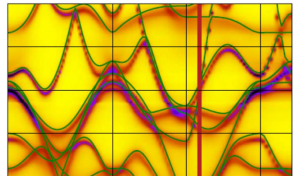
## 2. Atoms in crystals

- types of bonding
- elasticity and thermodynamics
- phonons (lattice vibrations)



## 3. Electrons in crystals

- free electron gas / Drude metal
- electronic band structure
- Fermi surface



Resistivity = specific resistance

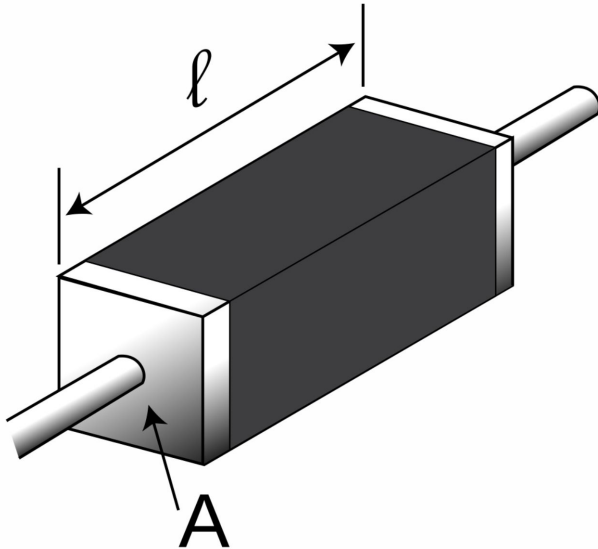


Image credit: Omegatron (CC-BY-SA)

ELEMENT	Z	$n$ ( $10^{22}/\text{cm}^3$ )
Li (78 K)	1	4.70
Na (5 K)	1	2.65
K (5 K)	1	1.40
Rb (5 K)	1	1.15
Cs (5 K)	1	0.91
Cu	1	8.47
Ag	1	5.86
Au	1	5.90
Be	2	24.7
Mg	2	8.61
Ca	2	4.61
Sr	2	3.55
Ba	2	3.15

**Z = 1**  
↓  
1

**Z = 2**  
↓  
2

3	6.94*	4	9.012						
<b>Li</b>		<b>Be</b>							
lithium		beryllium							
11	22.99	12	24.31*						
<b>Na</b>		<b>Mg</b>							
sodium		magnesium							
				3	4	5			
19	39.10	20	40.08	21	44.96	22	47.87	23	50.94
<b>K</b>		<b>Ca</b>		<b>Sc</b>		<b>Ti</b>		<b>V</b>	
potassium		calcium		scandium		titanium		vanadium	
37	85.47	38	87.62	39	88.91	40	91.22	41	92.91
<b>Rb</b>		<b>Sr</b>		<b>Y</b>		<b>Zr</b>		<b>Nb</b>	
rubidium		strontium		yttrium		zirconium		niobium	
55	132.9	56	137.3	57-71		72	178.5	73	180.9
<b>Cs</b>		<b>Ba</b>				<b>Hf</b>		<b>Ta</b>	
caesium		barium				hafnium		tantalum	

# Valence of metals

Image credit: László Németh (CC-zero)

The periodic table is color-coded by groups, with arrows indicating the number of valence electrons (Z) for each group:

- Z=1:** Red arrow pointing to Group 1 (alkali metals).
- Z=2:** Orange arrow pointing to Group 2 (alkaline earth metals).
- Z=3:** Green arrow pointing to Group 13 (boron group).
- Z=4:** Blue arrow pointing to Group 14 (carbon group).

1																		18																	
Z=1																		Z=2		Z=3		Z=4													
1																	2																		
<b>H</b>																	<b>He</b>																		
hydrogen																	helium																		
3		4														5		6		7		8		9		10									
<b>Li</b>	<b>Be</b>													<b>B</b>	<b>C</b>	<b>N</b>	<b>O</b>	<b>F</b>	<b>Ne</b>																
lithium	beryllium													boron	carbon	nitrogen	oxygen	fluorine	neon																
11		12														13		14		15		16		17		18									
<b>Na</b>	<b>Mg</b>													<b>Al</b>	<b>Si</b>	<b>P</b>	<b>S</b>	<b>Cl</b>	<b>Ar</b>																
sodium	magnesium													aluminium	silicon	phosphorus	sulfur	chlorine	argon																
19		20		21		22		23		24		25		26		27		28		29		30		31		32		33		34		35		36	
<b>K</b>	<b>Ca</b>	<b>Sc</b>	<b>Ti</b>	<b>V</b>	<b>Cr</b>	<b>Mn</b>	<b>Fe</b>	<b>Co</b>	<b>Ni</b>	<b>Cu</b>	<b>Zn</b>	<b>Ga</b>	<b>Ge</b>	<b>As</b>	<b>Se</b>	<b>Br</b>	<b>Kr</b>																		
potassium	calcium	scandium	titanium	vanadium	chromium	manganese	iron	cobalt	nickel	copper	zinc	gallium	germanium	arsenic	selenium	bromine	krypton																		
37		38		39		40		41		42		43		44		45		46		47		48		49		50		51		52		53		54	
<b>Rb</b>	<b>Sr</b>	<b>Y</b>	<b>Zr</b>	<b>Nb</b>	<b>Mo</b>	<b>Tc</b>	<b>Ru</b>	<b>Rh</b>	<b>Pd</b>	<b>Ag</b>	<b>Cd</b>	<b>In</b>	<b>Sn</b>	<b>Sb</b>	<b>Te</b>	<b>I</b>	<b>Xe</b>																		
rubidium	strontium	yttrium	zirconium	niobium	molybdenum	technetium	ruthenium	rhodium	palladium	silver	cadmium	indium	tin	antimony	tellurium	iodine	xenon																		
55		56		57-71		72		73		74		75		76		77		78		79		80		81		82		83		84		85		86	
<b>Cs</b>	<b>Ba</b>																	<b>Hf</b>	<b>Ta</b>	<b>W</b>	<b>Re</b>	<b>Os</b>	<b>Ir</b>	<b>Pt</b>	<b>Au</b>	<b>Hg</b>	<b>Tl</b>	<b>Pb</b>	<b>Bi</b>	<b>Po</b>	<b>At</b>	<b>Rn</b>			
caesium	barium																	hafnium	tantalum	tungsten	rhenium	osmium	iridium	platinum	gold	mercury	thallium	lead	bismuth	polonium	astatine	radon			
87		88		89-103		104		105		106		107		108		109		110		111		112		113		114		115		116		117		118	
<b>Fr</b>	<b>Ra</b>																	<b>Rf</b>	<b>Db</b>	<b>Sg</b>	<b>Bh</b>	<b>Hs</b>	<b>Mt</b>	<b>Ds</b>	<b>Rg</b>	<b>Cn</b>	<b>Nh</b>	<b>Fl</b>	<b>Mc</b>	<b>Lv</b>	<b>Ts</b>	<b>Og</b>			
francium	radium																	rutherfordium	dubnium	seaborgium	bohrium	hassium	meitnerium	darmstadtium	roentgenium	copernicium	nihonium	flerovium	moscovium	livermorium	tennessine	oganeson			
57		58		59		60		61		62		63		64		65		66		67		68		69		70		71		72					
<b>La</b>	<b>Ce</b>	<b>Pr</b>	<b>Nd</b>	<b>Pm</b>	<b>Sm</b>	<b>Eu</b>	<b>Gd</b>	<b>Tb</b>	<b>Dy</b>	<b>Ho</b>	<b>Er</b>	<b>Tm</b>	<b>Yb</b>	<b>Lu</b>																					
lanthanum	cerium	praseodymium	neodymium	promethium	samarium	europium	gadolinium	terbium	dysprosium	holmium	erbium	thulium	ytterbium	lutetium																					
89		90		91		92		93		94		95		96		97		98		99		100		101		102		103		104					
<b>Ac</b>	<b>Th</b>	<b>Pa</b>	<b>U</b>	<b>Np</b>	<b>Pu</b>	<b>Am</b>	<b>Cm</b>	<b>Bk</b>	<b>Cf</b>	<b>Es</b>	<b>Fm</b>	<b>Md</b>	<b>No</b>	<b>Lr</b>																					
actinium	thorium	protactinium	uranium	neptunium	plutonium	americium	curium	berkelium	californium	einsteinium	fermium	mendelevium	nobelium	lawrencium																					

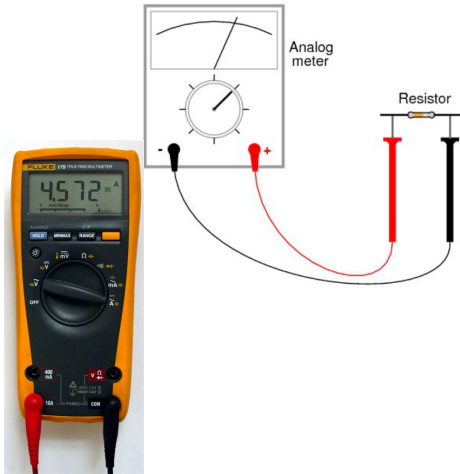
Resistivity:  $\rho$  ( $10^{-8} \Omega \cdot \text{m}$ )

ELEMENT	77 K	273 K	373 K	
Li	1.04	8.55	12.4	$n_e$ ↑ <b>Z = 1</b>
Na	0.8	4.2	Melted	
K	1.38	6.1	Melted	
Rb	2.2	11.0	Melted	
Cs	4.5	18.8	Melted	
Cu	0.2	1.56	2.24	
Ag	0.3	1.51	2.13	$n_e$ ↑ <b>Z = 2</b>
Au	0.5	2.04	2.84	
Be		2.8	5.3	
Mg	0.62	3.9	5.6	
Ca		3.43	5.0	
Sr	7	23		
Ba	17	60		



# Experimental technique

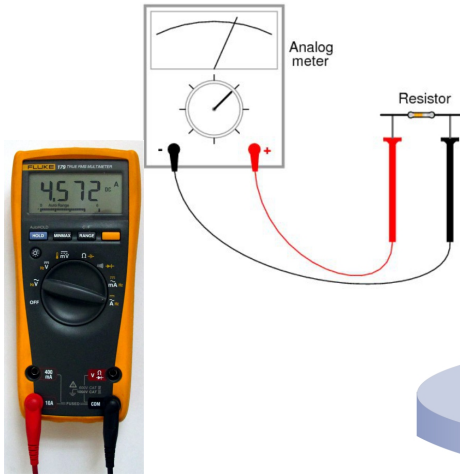
*resistivity measurements*



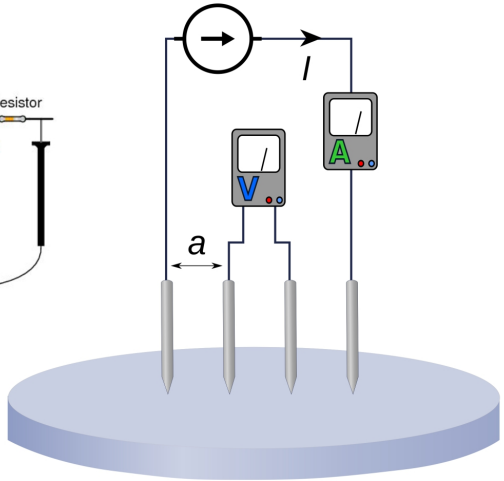
Two-probe method



# Two-probe vs. four-probe



Two-probe method  
**contact resistance**



Four-probe method

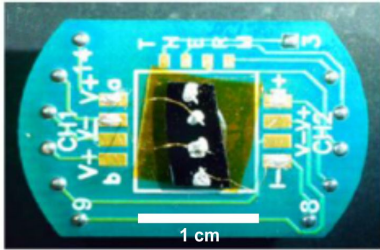


Image credits: Seyed Majid Mohseni (PhD thesis); Archives Biochem. Biophys. 581, 122 (2015); npj 2D Mater. Appl. 4, 7 (2020)

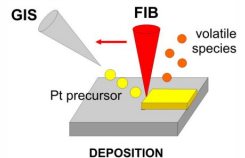
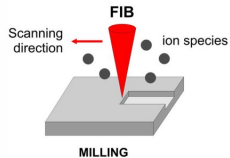
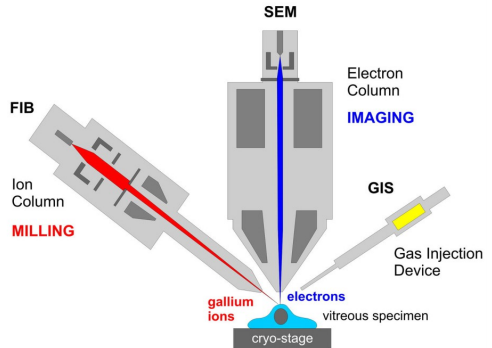
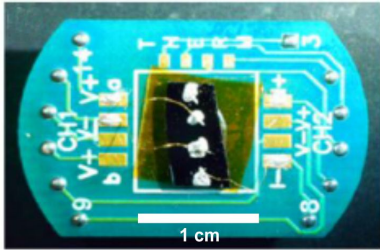


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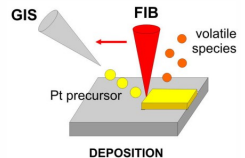
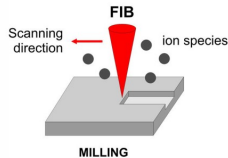
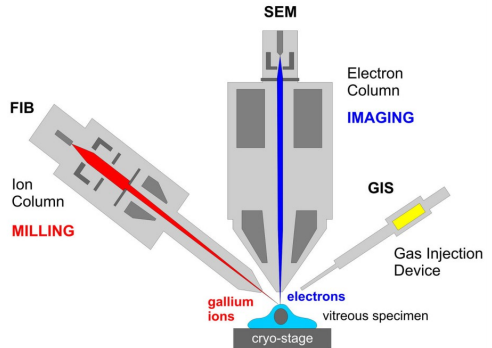
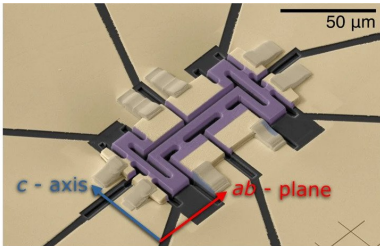
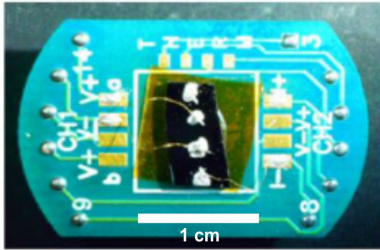


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ELEMENT	273 K		373 K	
	$\kappa$ (watt/cm-K)	$\kappa/\sigma T$ (watt-ohm/K <sup>2</sup> )	$\kappa$ (watt/cm-K)	$\kappa/\sigma T$ (watt-ohm/K <sup>2</sup> )
Li	0.71	$2.22 \times 10^{-8}$	0.73	$2.43 \times 10^{-8}$
Na	1.38	2.12		
K	1.0	2.23		
Rb	0.6	2.42		
Cu	3.85	2.20	3.82	2.29
Ag	4.18	2.31	4.17	2.38
Au	3.1	2.32	3.1	2.36
Be	2.3	2.36	1.7	2.42
Mg	1.5	2.14	1.5	2.25
Nb	0.52	2.90	0.54	2.78
Fe	0.80	2.61	0.73	2.88
Zn	1.13	2.28	1.1	2.30



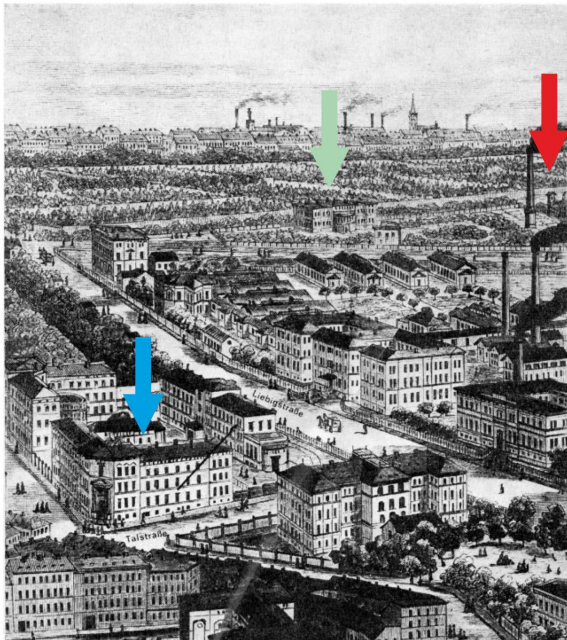
Person

*Paul Drude*



Paul Drude  
1863–1906

- 1880's: studied mathematics and physics in Göttingen
- 1887: PhD on reflection and diffraction of light in crystals
- 1894–1900: associate professor in Leipzig
- 1890's: optical properties of metals
- 1900: formulated first theory of metals (Drude model)



**new building  
(Linnéstraße)  
opens 1905**

**botanical garden**

**old building  
(Talstraße 35)**

Image source: Ann. Phys. (Leipzig) 15, 449 (2006)





Paul Drude  
1863–1906

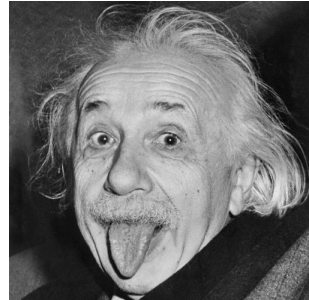
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- 1887: PhD on reflection and diffraction of light in crystals
- 1894–1900: professor in Leipzig
- 1890's: optical properties of metals
- 1900: formulated first theory of metals (renowned Drude model)
- 1901–1905: professor in Giessen
- since 1905: director of the Physics Institute in Berlin
- 1906: member of the Prussian Academy of Sciences



Paul Drude  
1863–1906

Albert Einstein  
about Paul Drude:

Albert Einstein  
1879–1955



“What you say about German professors is unfortunately true. Drude discarded two objections, which I raised against his theory and which demonstrate a direct mistake in his conclusions, by pointing out that another (infallible) colleague of his shares his opinion.

**Authority gone to one's head is the greatest enemy of truth”**

# Physics Colloquium

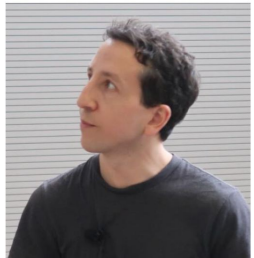
Tuesday, 12 Dec 2023 at 16:30

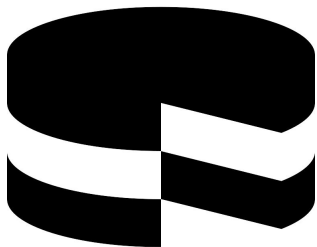
**Prof. Dr. Krzysztof Wohlfeld**

University of Warsaw

## **Spinons or magnons? A quest for the correct quasiparticle description of quantum magnets**

One of the main paradigms of quantum magnetism is that collective excitations in systems with long-range order, such as ferro/antiferro-magnets, are well described in terms of bosonic quasiparticles – magnons. This approach is extremely successful, since these magnons interact very weakly. On the other hand, once the long-range order collapses, for instance due to geometric frustration of spin couplings, magnons interact and such a description seems to fail. In contrast, the low-energy magnetic excitations are typically described in terms of fermionic spinons. Unfortunately, the latter quasiparticles are less intuitive, for they carry fractional quantum numbers and, most of the time, they also do interact.





# Material

*Thermoelectrics*

# Thermocouple (Seebeck effect)

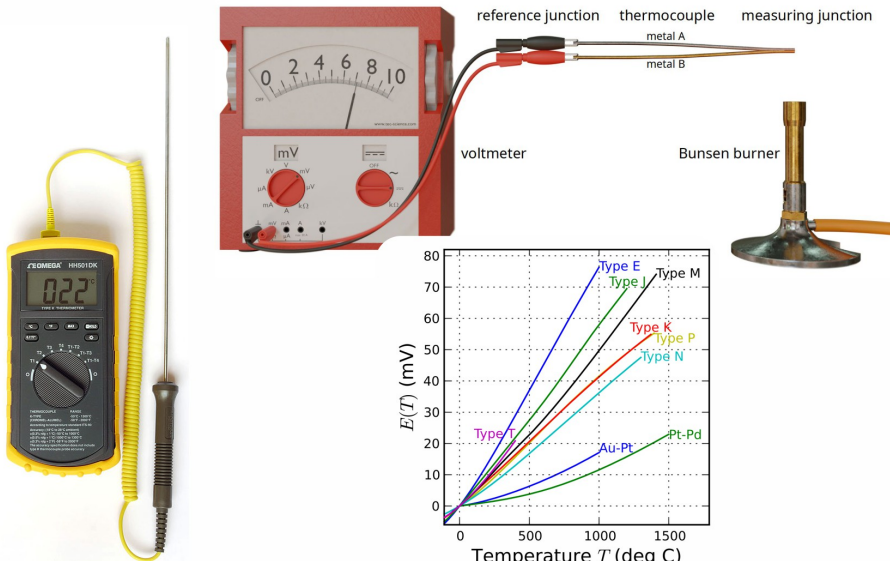


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