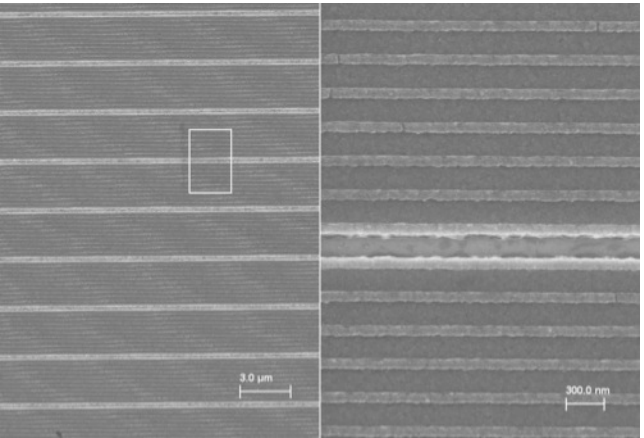


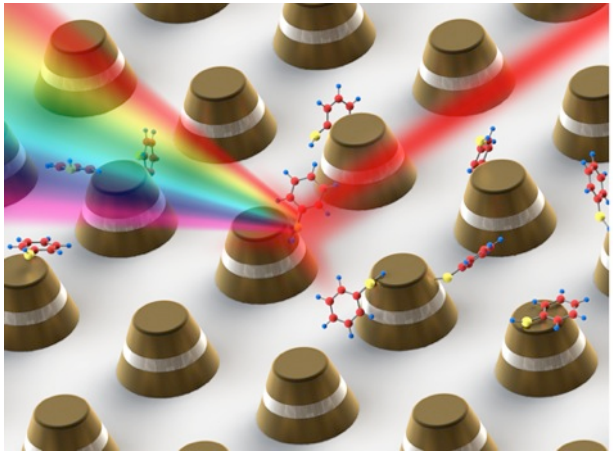
Quantum Mechanics in Functional Devices

Prof. Dr. Ekmel Ozbay

Nanotechnology Research Center (NANOTAM)

Bilkent University, Ankara, TURKEY



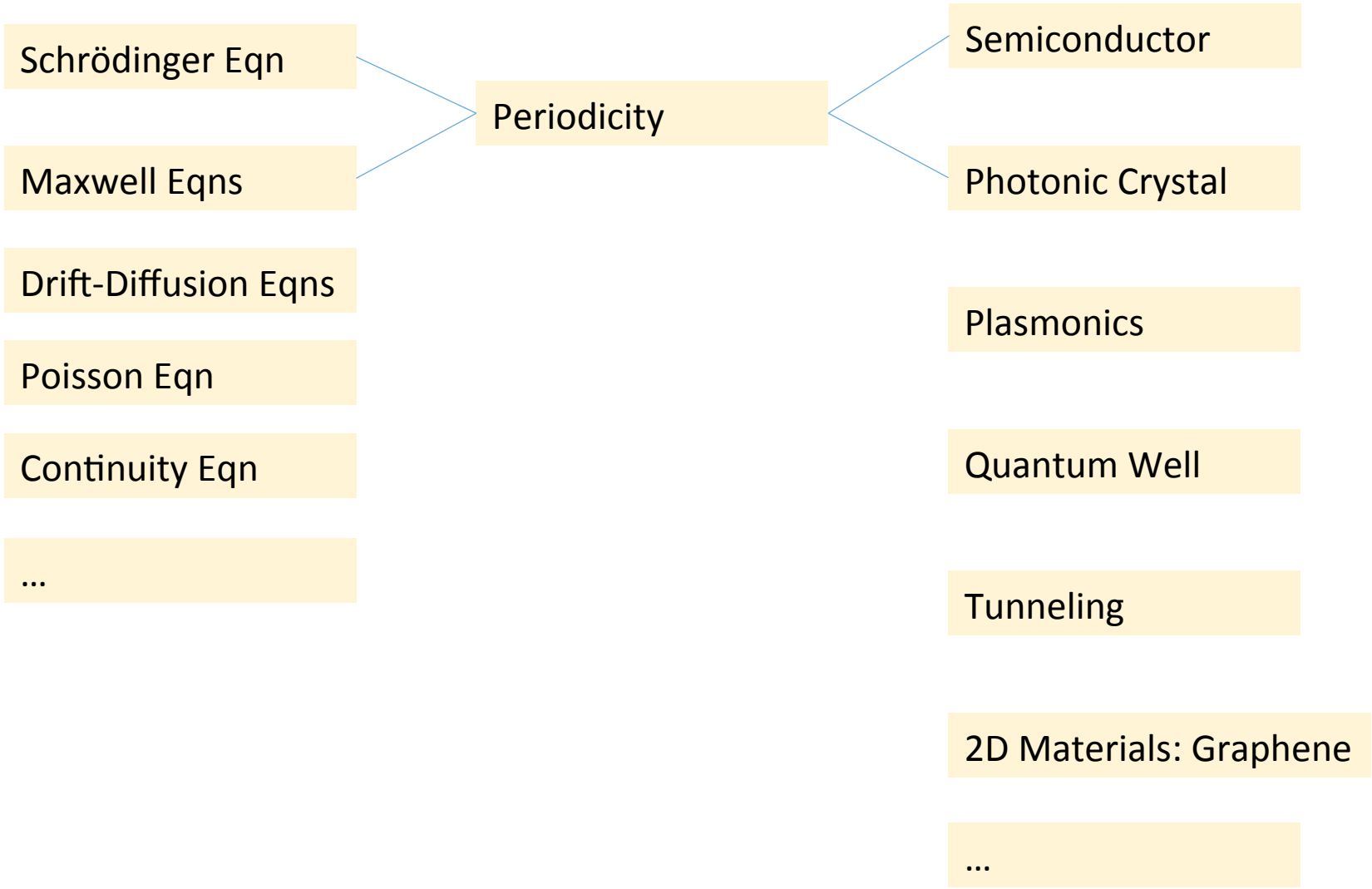


Contents

Research at Bilkent University Nanotechnology Research Center

- Equations that we are working with
- Materials that we are working with
- Devices that we are working on
- Selected Devices
  - 2D Electron Gas to Transistors: HEMT
  - Quantum Wells, Superlattices, and Light: Quantum Cascade Laser
  - 2D Crystal to Dirac Fermions: Graphene Transistor

Foundations: Equations that we are working with



Building Blocks: Materials that we are working with

GaAs

GaN

Si

ZnO

SiC

C

$LiNbO_3$

SnO_2

AlGaAs

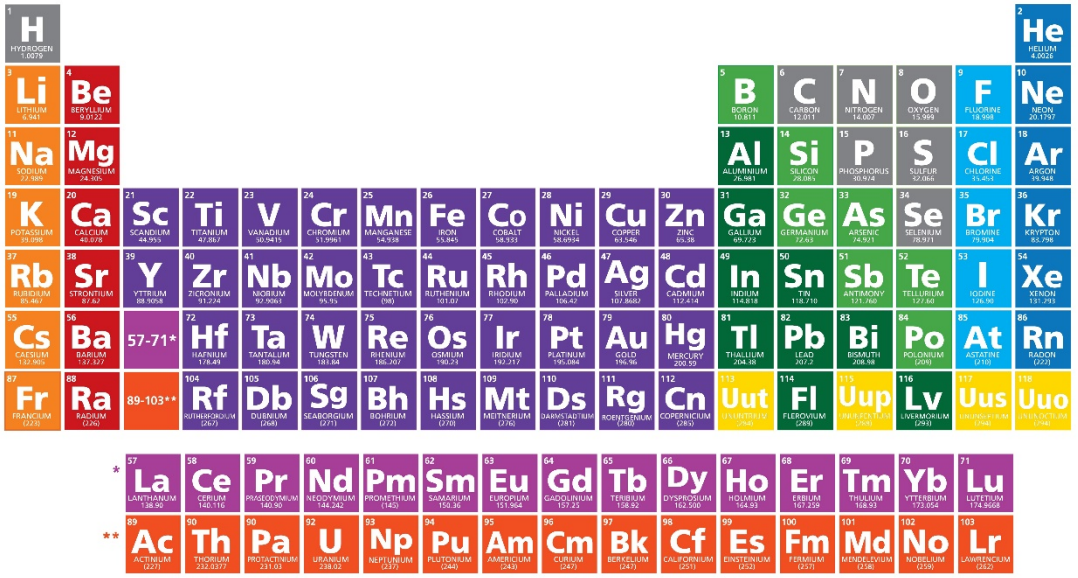
InGaN

AlAs

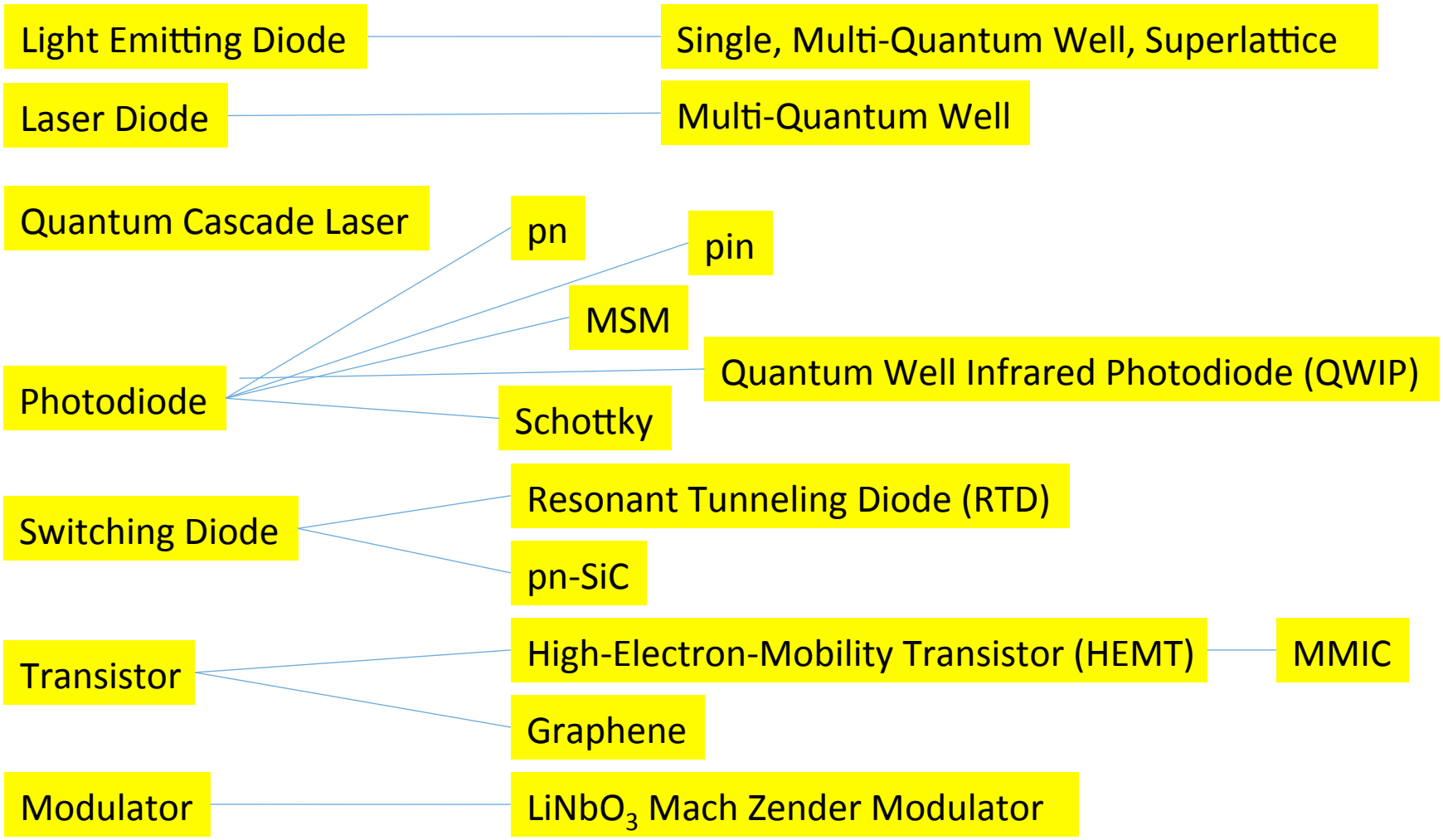
AlGaN

InGaAsP

InP



Building Blocks: Devices that we are working on



2D Electron Gas to Transistors: High electron mobility transistor (HEMT)

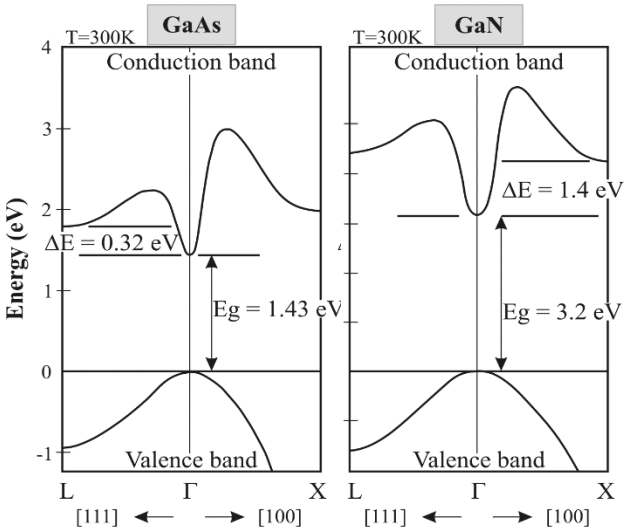
Also known as:

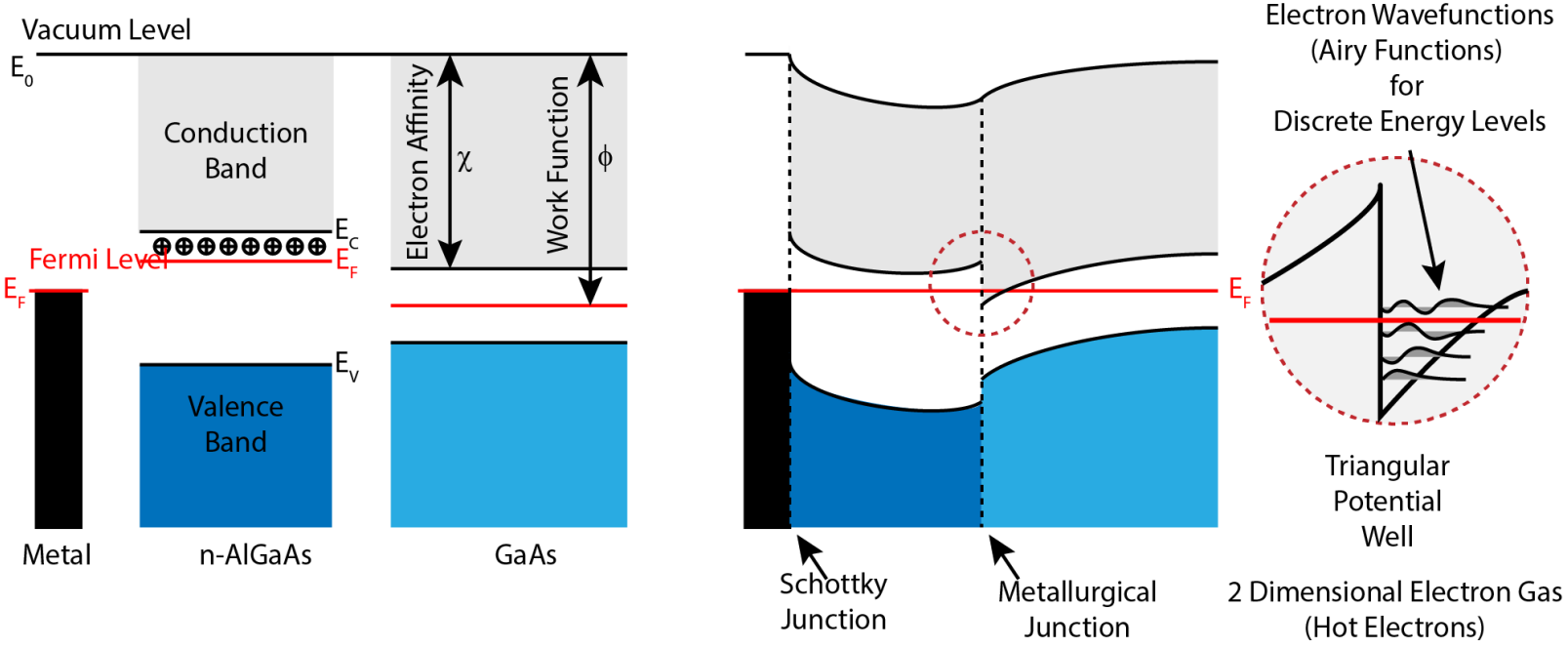
- **Heterojunction FET (HFET)**
- **Modulation doped field effect transistor (MODFET)**
- **Two-dimensional electron-gas FET (TEGFET)**
- **Selectively doped heterojunction transistor (SDHT)**

Unique energy band structure:

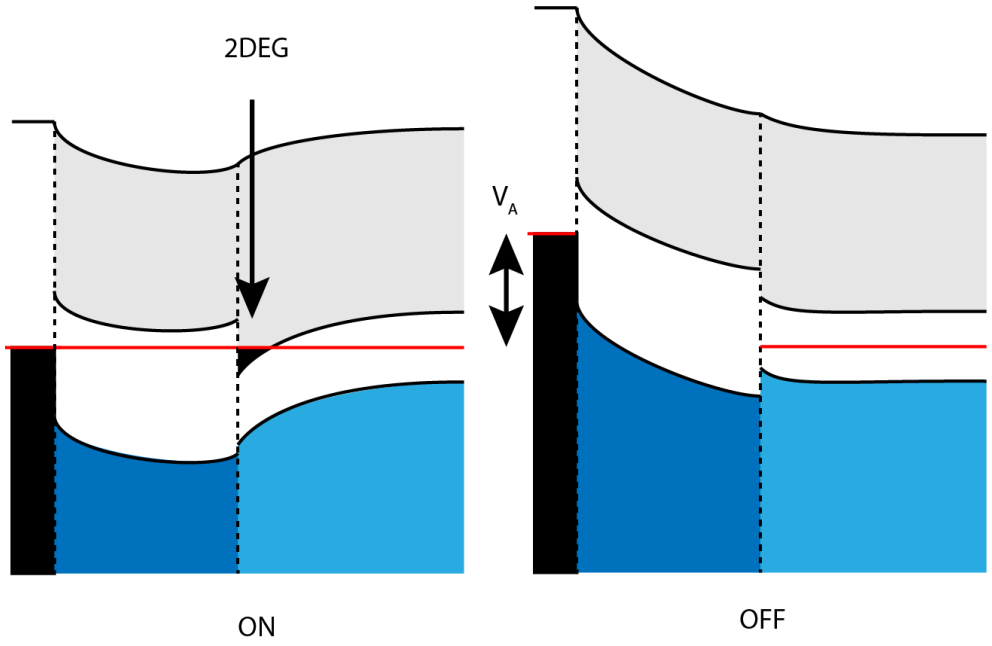
- **Two dimensional electron gas (2-DEG)**
- **Current path parallel to the channel (Esaki, Tsu 1969)**
- **High mobility in channel (no impurity scattering)**
- **Only one type of carriers (electrons) carries current**

HEMT

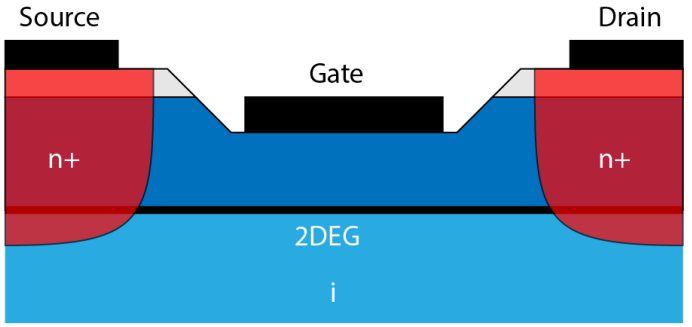

GaAs
T=300K
Conduction band
Valence band
ΔE = 0.32 eV
Eg = 1.43 eV
Energy (eV)
4
3
2
1
0
-1
L
Γ
X
[111]
[100]
GaN
T=300K
Conduction band
Valence band
ΔE = 1.4 eV
Eg = 3.2 eV
L
Γ
X
[111]
[100]

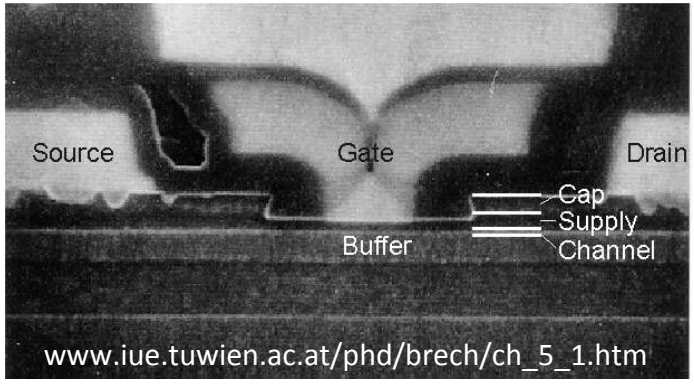

Vacuum Level
E0
Conduction Band
EC
Fermi Level
EF
EF
EV
Valence Band
Electron Affinity
χ
Work Function
ϕ
Metal
n-AlGaAs
GaAs
Schottky Junction
Metallurgical Junction
EF
Electron Wavefunctions (Airy Functions) for Discrete Energy Levels
Triangular Potential Well
2 Dimensional Electron Gas (Hot Electrons)

High Electron Mobility Transistor (HEMT)



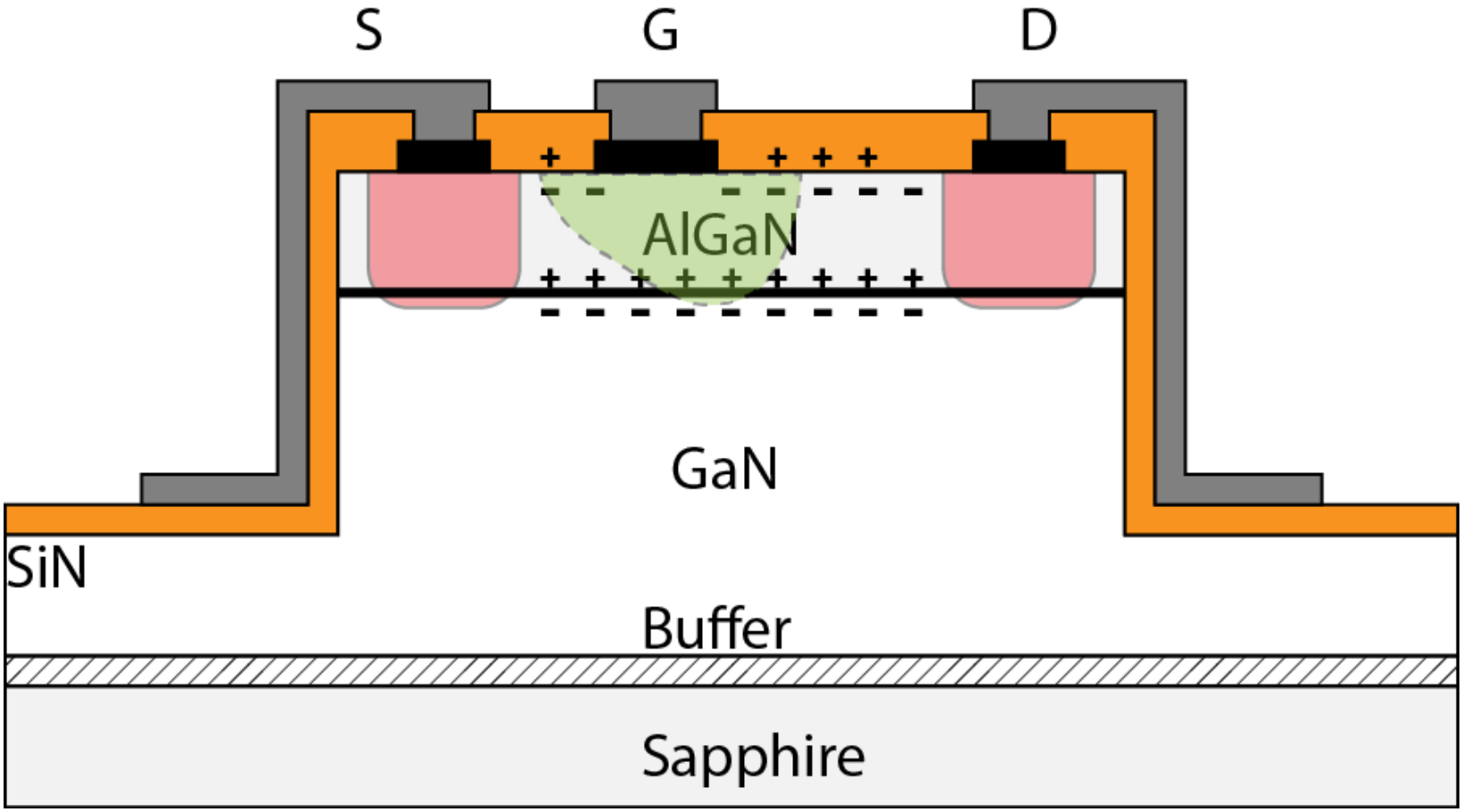
ON-OFF Energy Band Diagrams of a HEMT





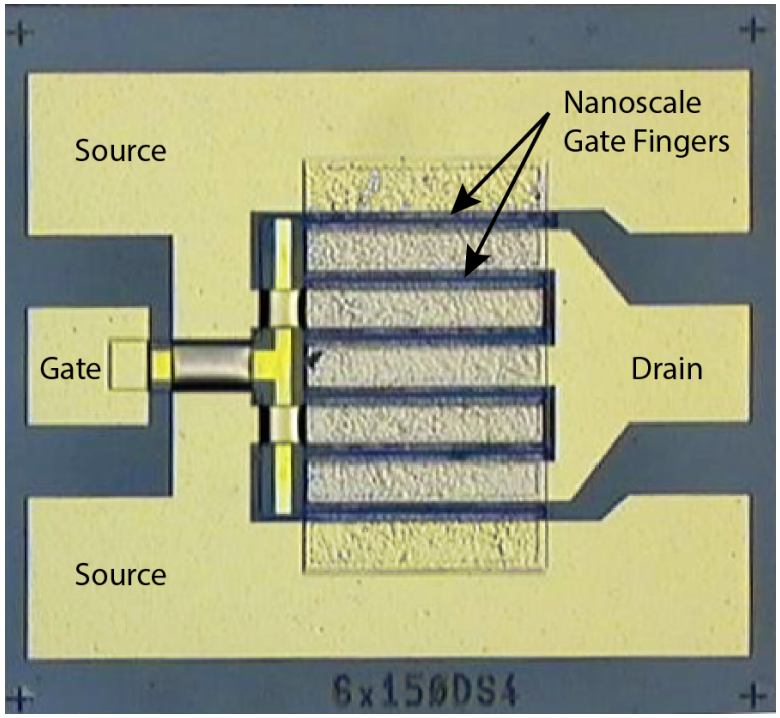
Lateral structure of HEMT, fabricated with recess etch

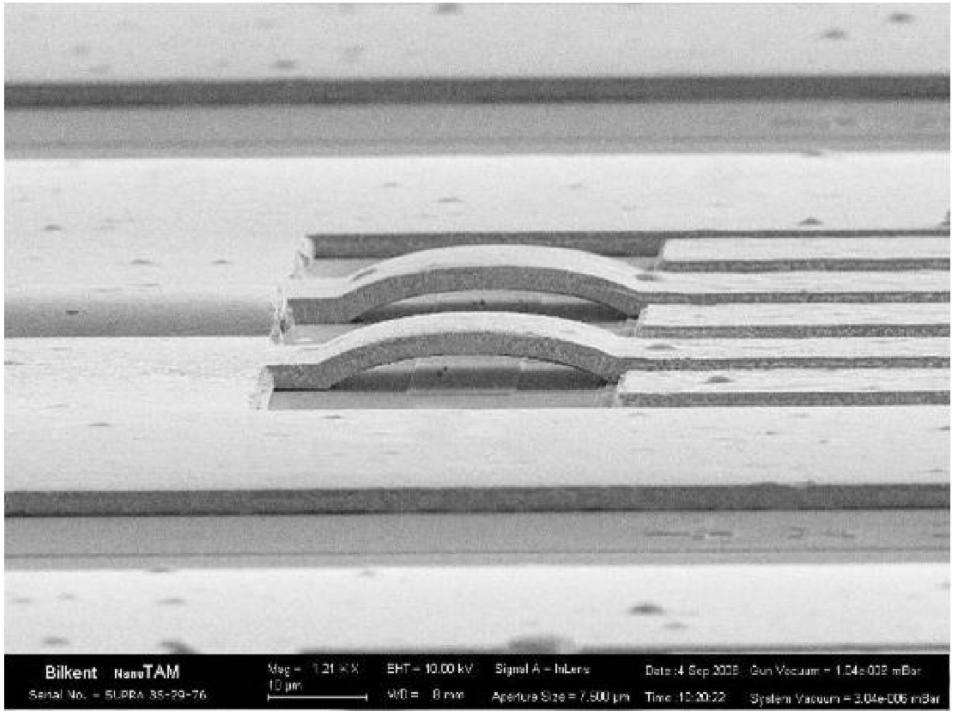
High Electron Mobility Transistor (HEMT)



High Electron Mobility Transistor (HEMT)

- **Gallium Nitride HEMT**
  - **High power (500W)**
  - **High frequency (~THz)**

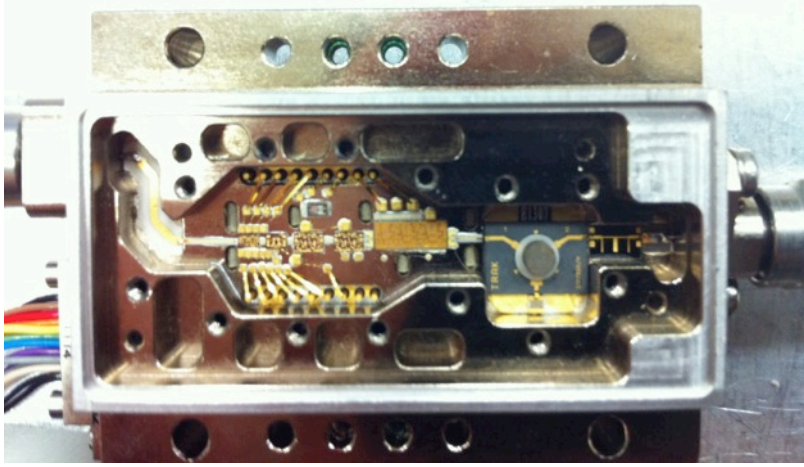


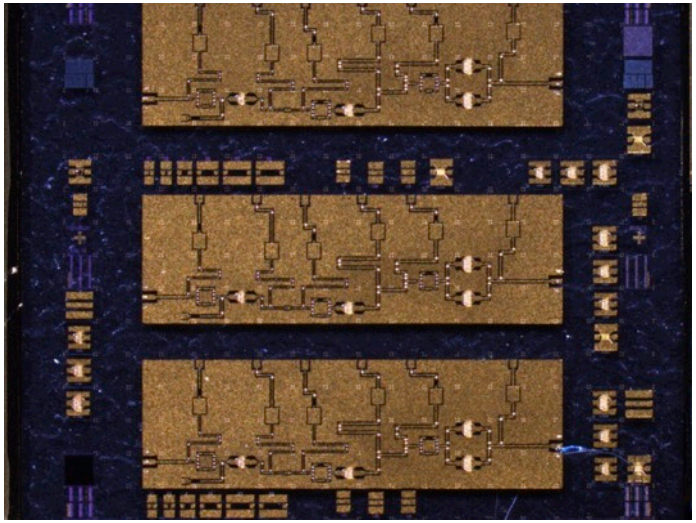


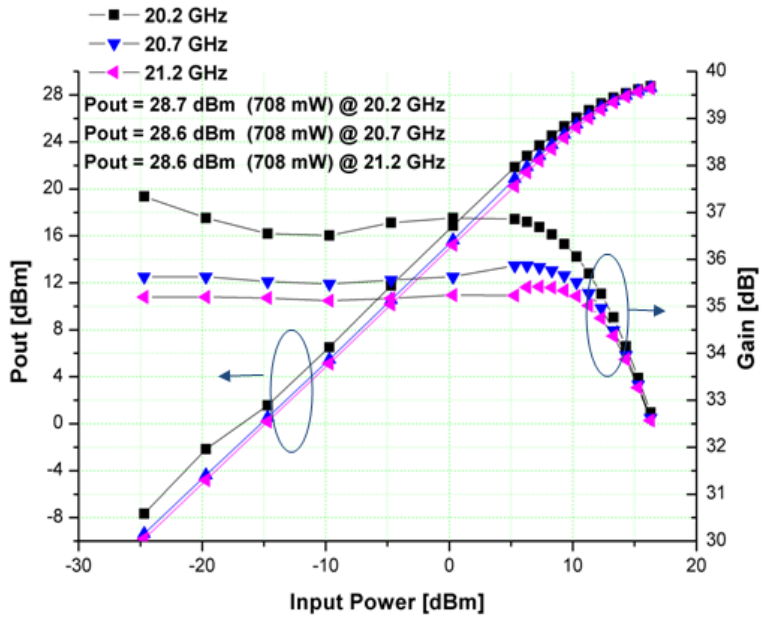
GaN based High Power MMICs for Space and Terrestrial Applications

Functional EHF Transponder

- Turkish Armed Forces (SSM) and TUBITAK
- Geosynchronous satellite based communication
- GaN MMICs in Space
- 38 Million USD budget (Bilkent)







Quantum Cascade Laser: Quantum Wells, Superlattices, and Light

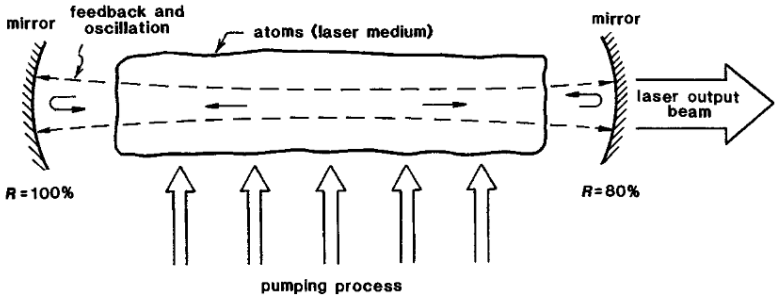
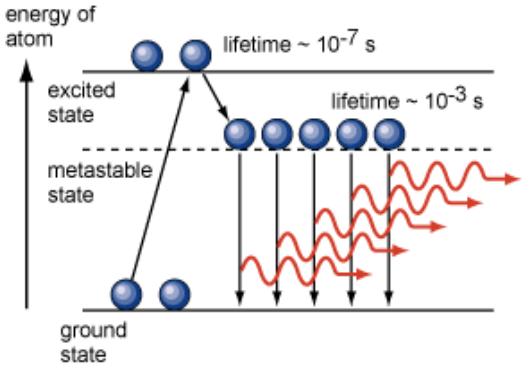
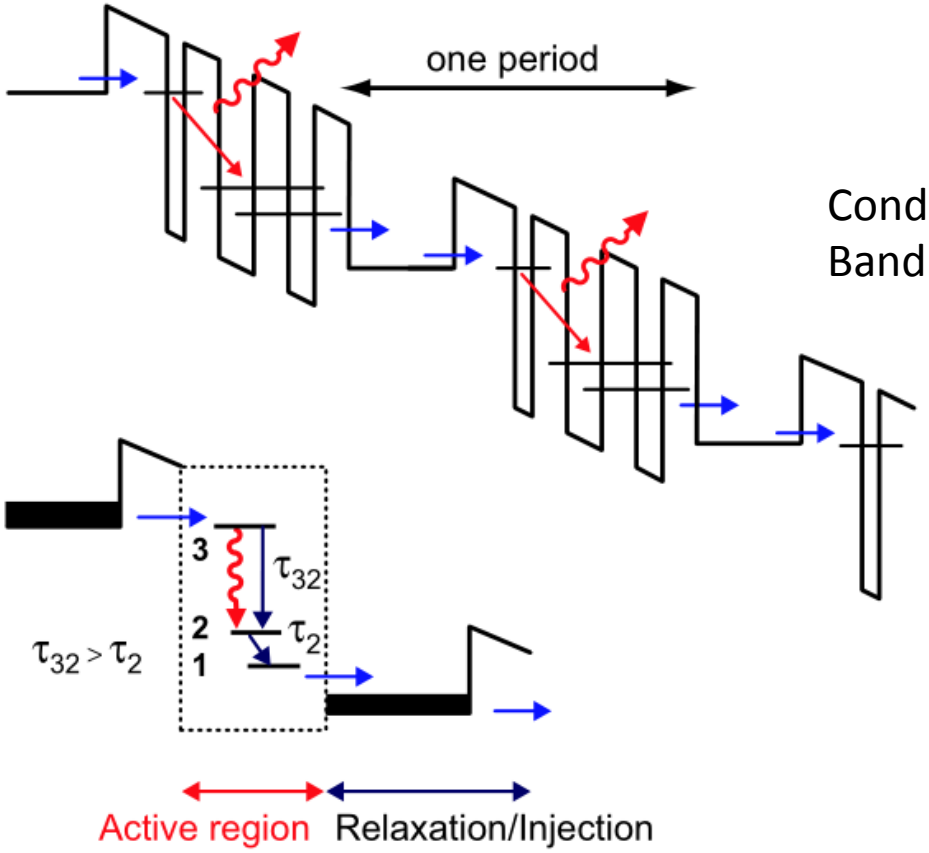
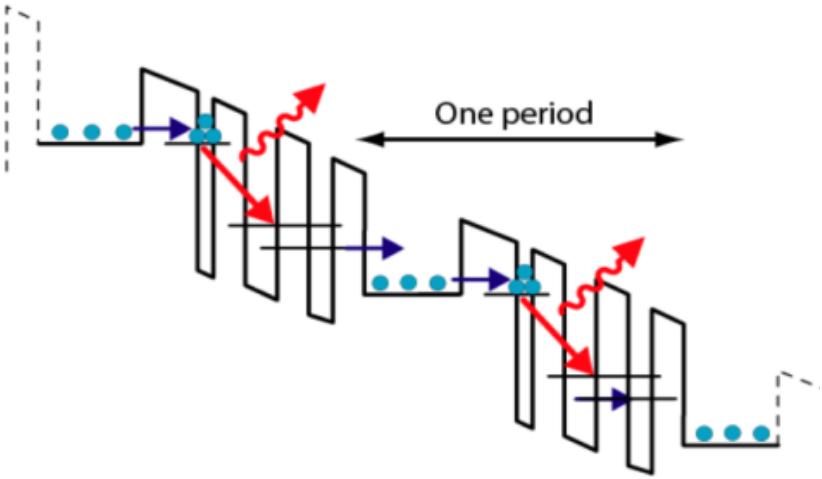


FIGURE 1.1
Elements of a typical laser oscillator.

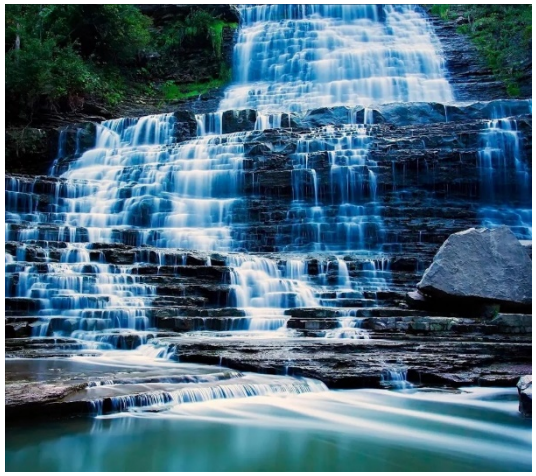


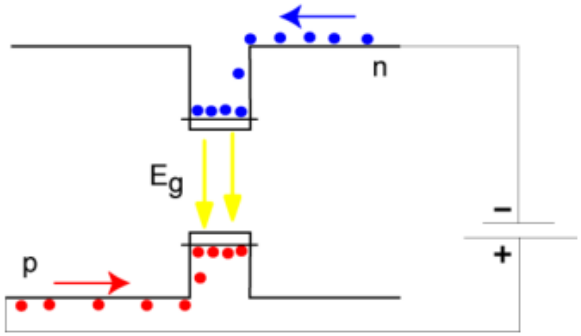


Quantum Cascade Laser: Designer lasers where you can choose the energy of the outcoming photons



Intersubband cascade laser

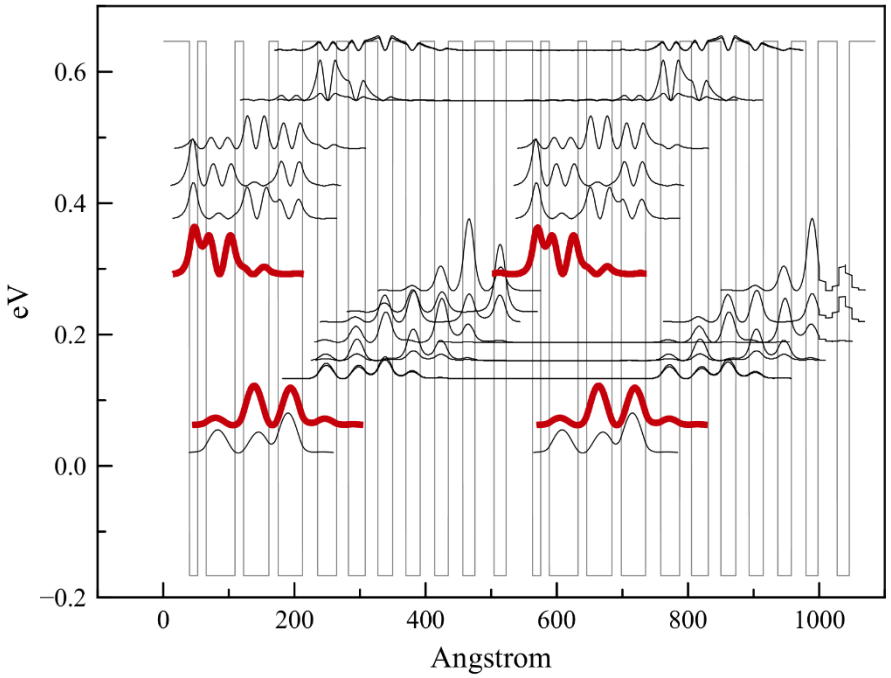




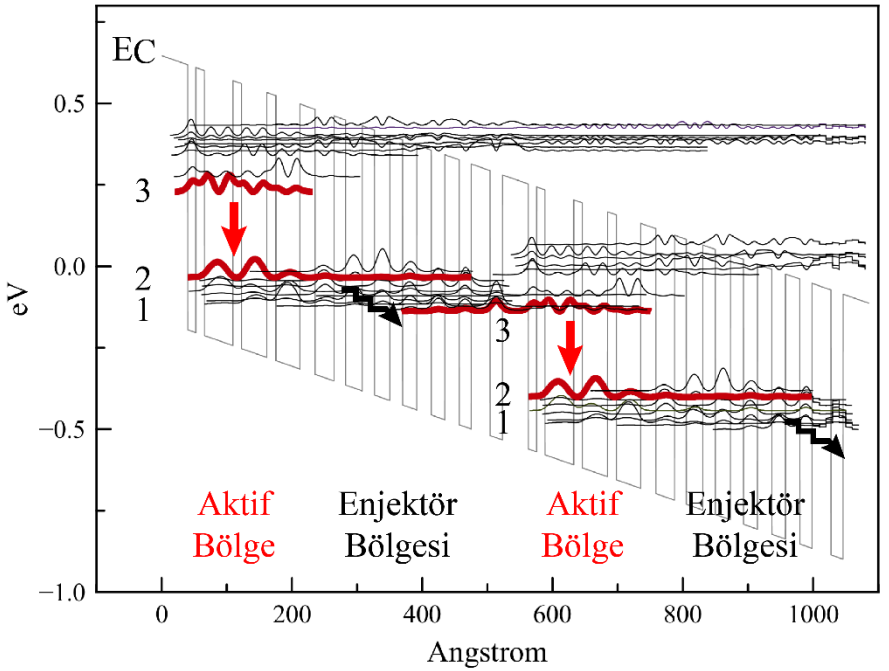
Interband laser diode

- 2.7–24μm, 84-100 μm on (AlInAs/InGaAs)InP
- 8–23 μm & 64–320 μm on (AlGaAs/GaAs)GaAs

QCL: Design, Active Region

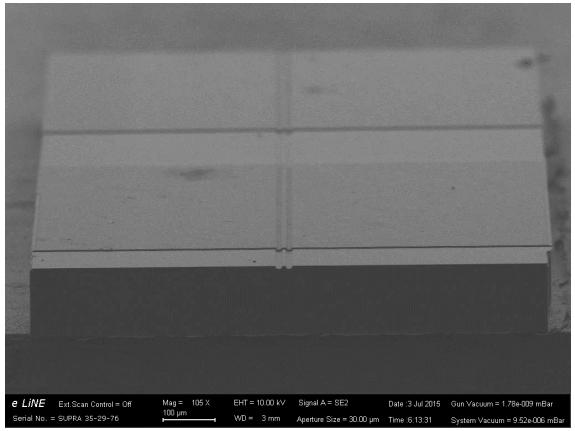


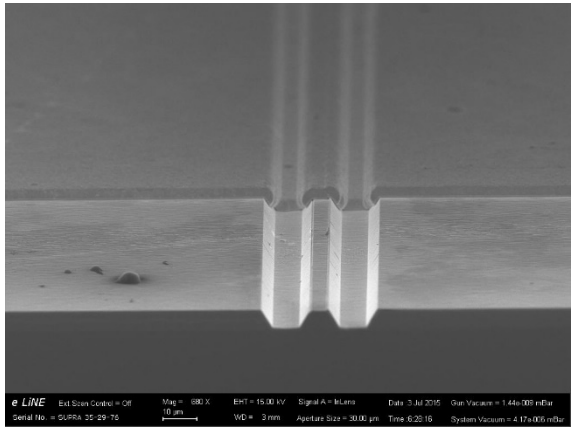
E-Field = 0

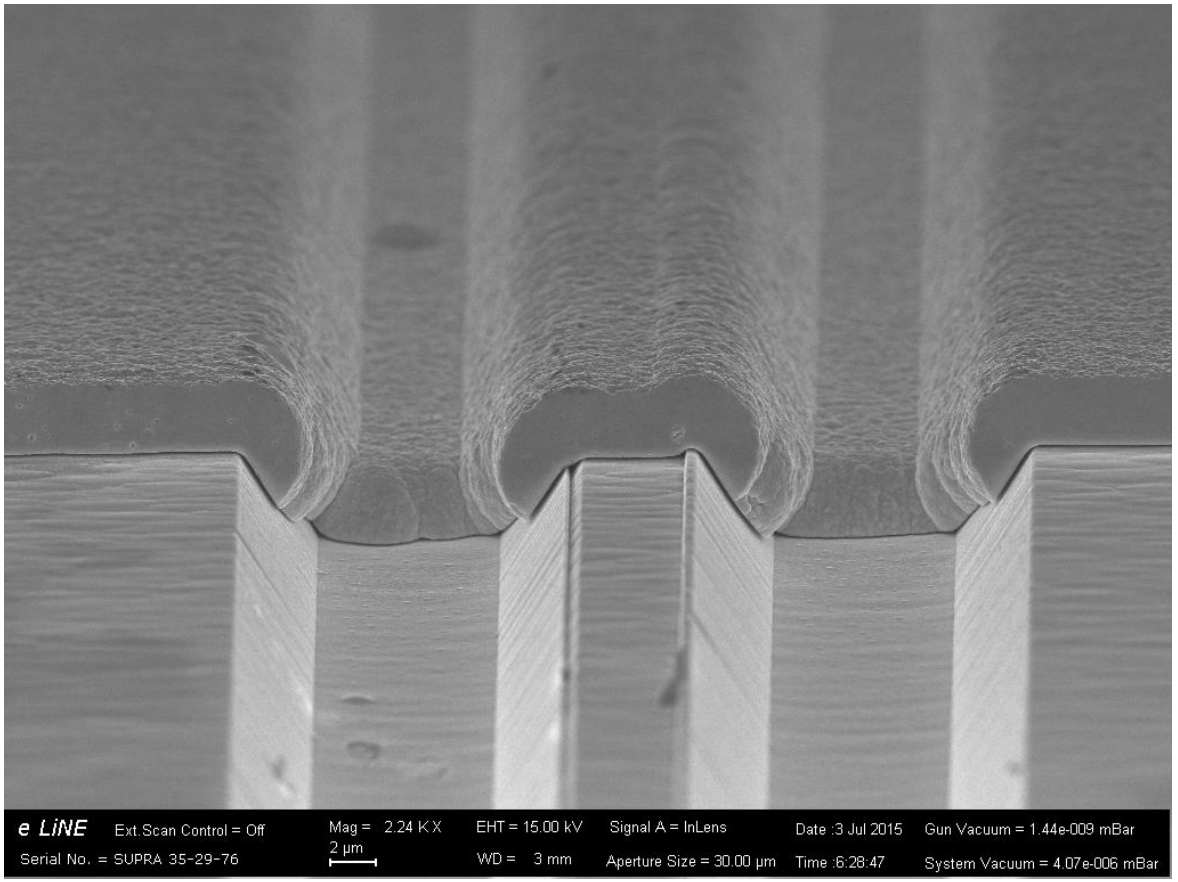


E-Field Applied

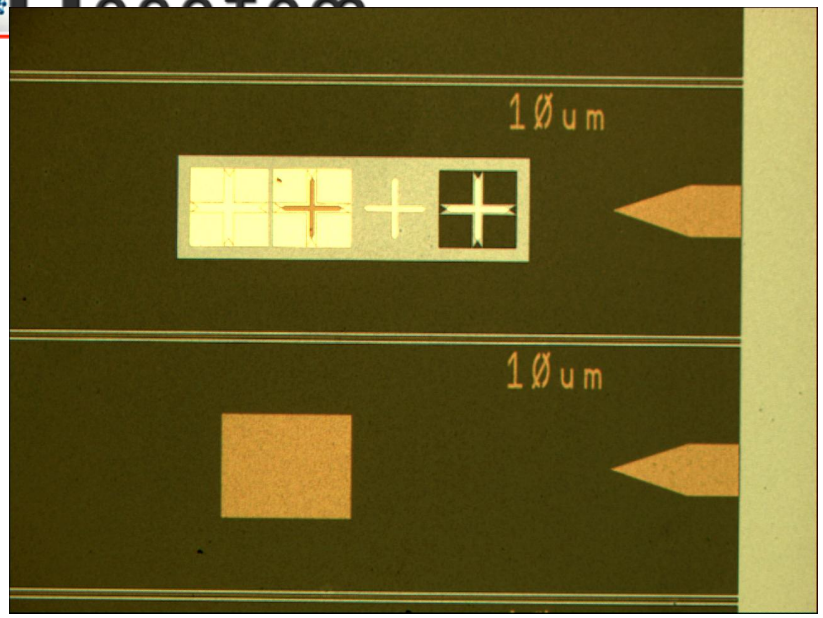
QCL: Fabrication and Measurement

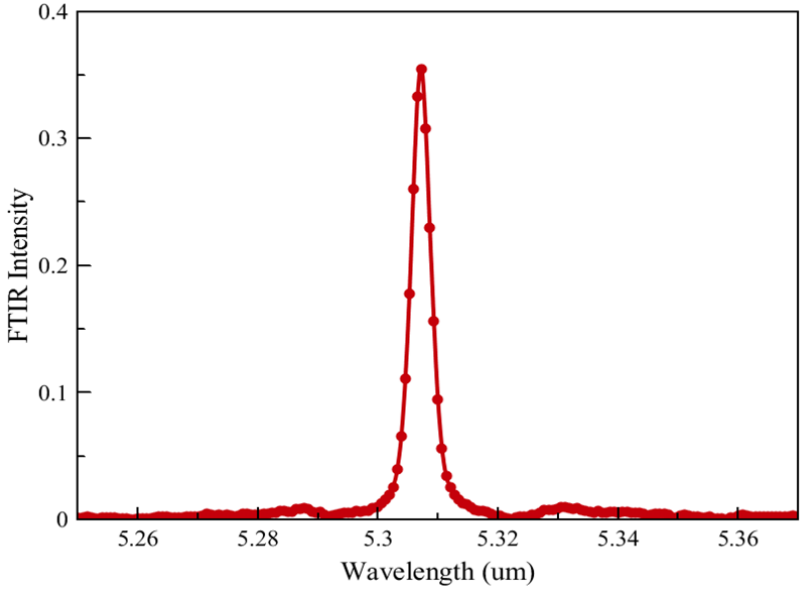


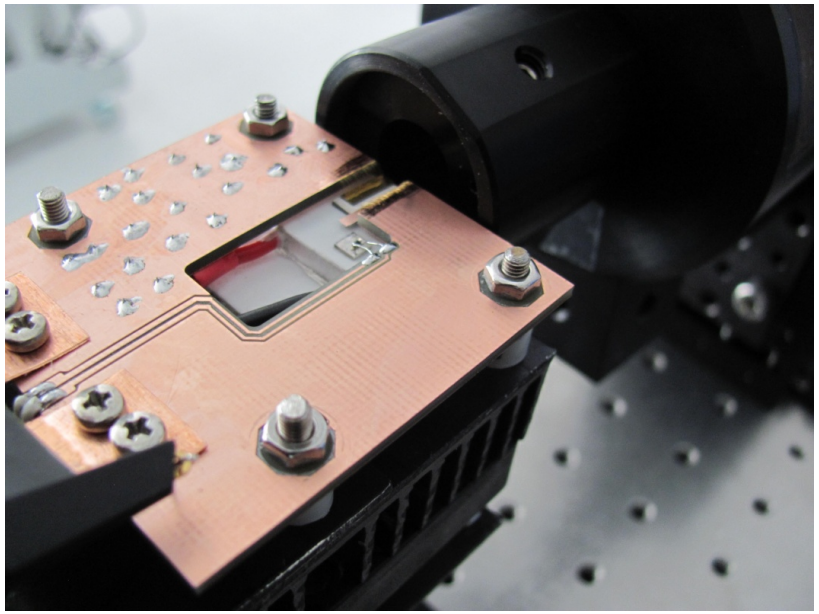


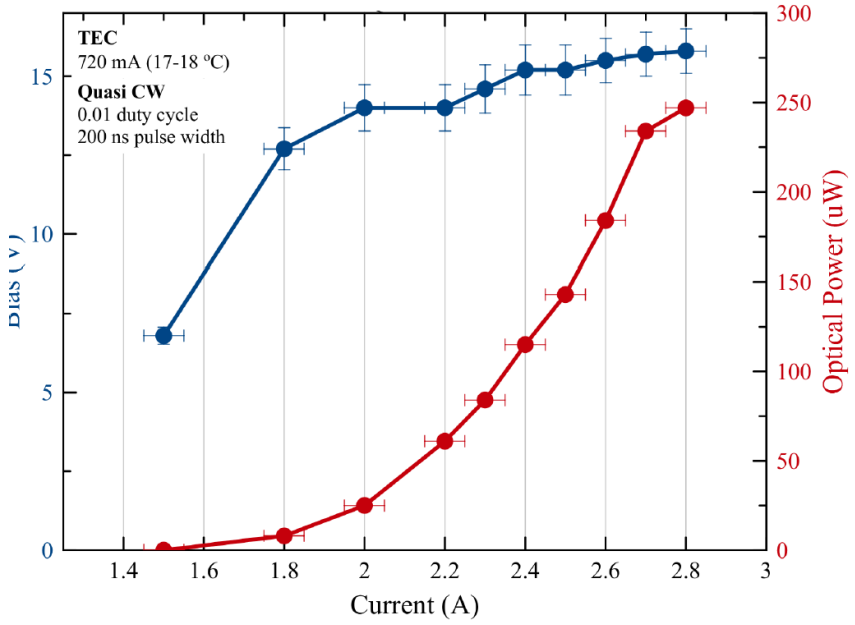


Fabricated QCL Structures


10um
10um

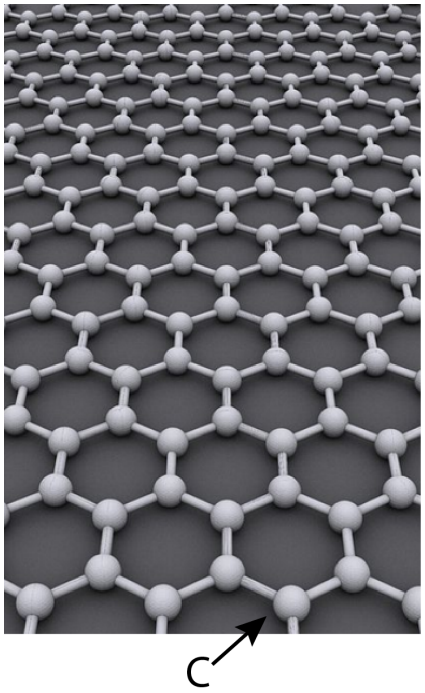

FTIR Intensity
Wavelength (um)
0.4
0.3
0.2
0.1
0
5.26
5.28
5.3
5.32
5.34
5.36

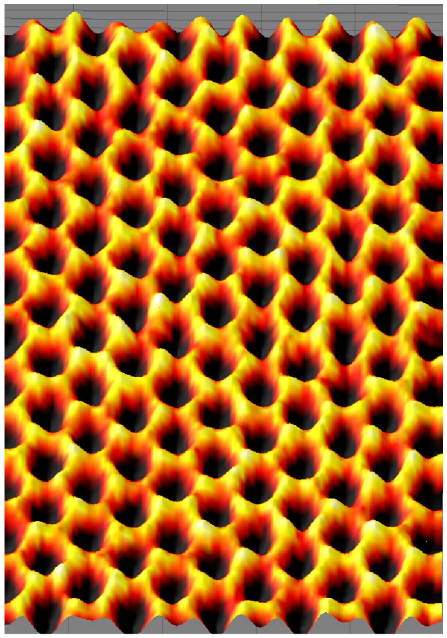



TEC
720 mA (17-18 ºC)
Quasi CW
0.01 duty cycle
200 ns pulse width
Optical Power (uW)
Current (A)
15
10
5
0
300
250
200
150
100
50
0
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3

Graphene: 2D Crystal to Dirac Fermions

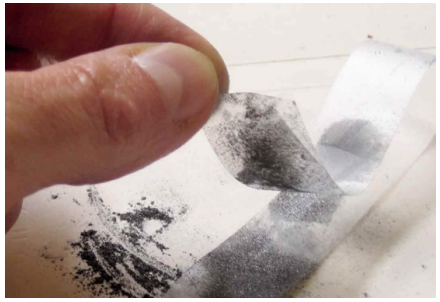
An allotrope of carbon in the form of a two-dimensional, atomic-scale, honey-comb lattice in which one atom forms each vertex.

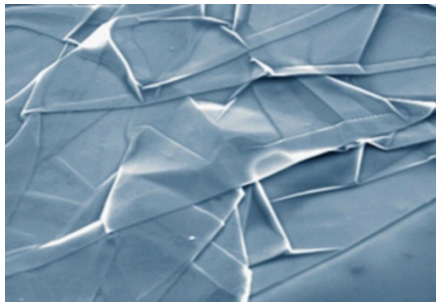




SPM Image







- **'Its charge carriers mimic relativistic particles and are more easily and naturally described starting with the Dirac equation rather than the Schrödinger equation.'**
- **'Although there is nothing particularly relativistic about electrons moving around carbon atoms, their interaction with the periodic potential of graphene's honeycomb lattice gives rise to new quasiparticles: Dirac Fermions'**
  - **i.e.: electrons that have lost their rest mass m_0 or as neutrinos that acquired the electron charge e.**
  - **direct consequence of graphene's crystal symmetry.**

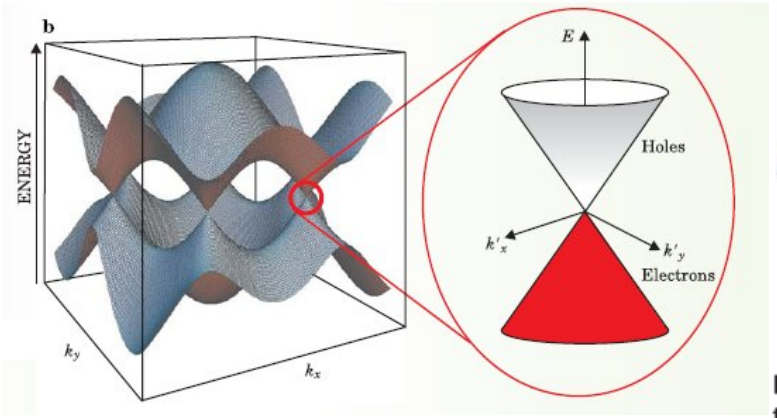
Dirac-like Hamiltonian

$$\hat{H} = \hbar v_F \begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix} = \hbar v_F \, \boldsymbol{\sigma} \cdot \mathbf{k}$$

k is the quasiparticle momentum, σ the 2D Pauli matrix and the k-independent Fermi velocity v_F plays the role of the speed of light.

A. K. Geim, K. S. Novoselov, Nature, 2007
doi:10.1038/nmat1849

Graphene Band Structure



Graphene

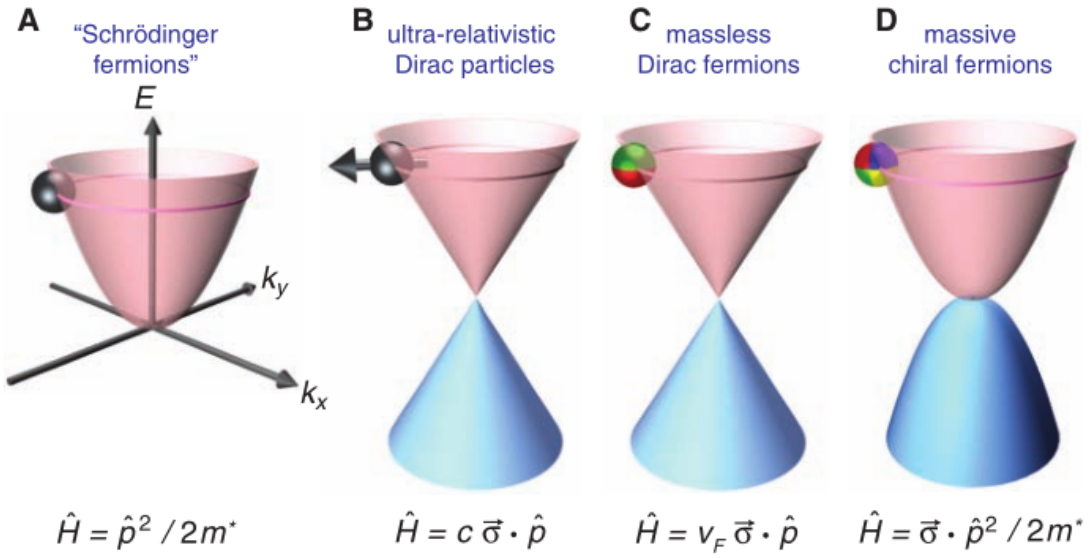
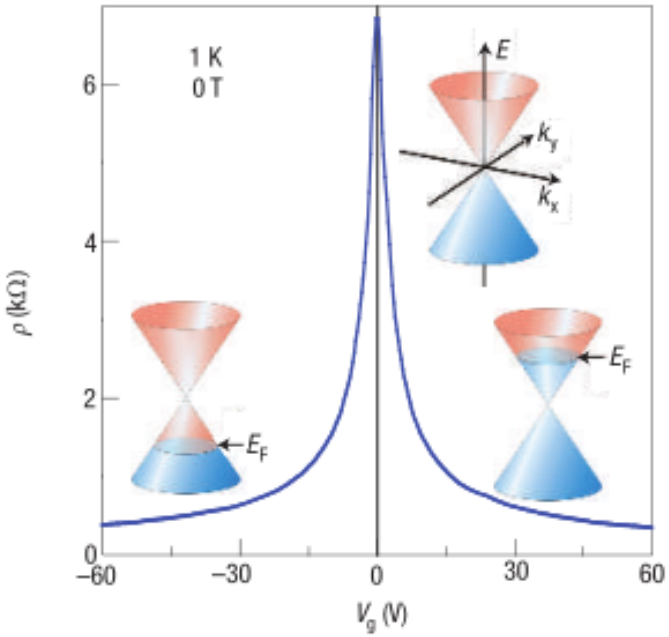


Fig. 2. Quasi-particle zoo. (**A**) Charge carriers in condensed matter physics are normally described by the Schrödinger equation with an effective mass m^* different from the free electron mass ($\hat{p}$ is the momentum operator). (**B**) Relativistic particles in the limit of zero rest mass follow the Dirac equation, where c is the speed of light and $\vec{\sigma}$ is the Pauli matrix. (**C**) Charge carriers in graphene are called massless Dirac fermions and are described by a 2D analog of the Dirac equation, with the Fermi velocity $v_F \approx 1 \times 10^6$ m/s playing the role of the speed of light and a 2D pseudospin matrix $\vec{\sigma}$ describing two sublattices of the honeycomb lattice (*3*). Similar to the real spin that can change its direction between, say, left and right, the pseudospin is an index that indicates on which of the two sublattices a quasi-particle is located. The pseudospin can be indicated by color (e.g., red and green). (**D**) Bilayer graphene provides us with yet another type of quasi-particles that have no analogies. They are massive Dirac fermions described by a rather bizarre Hamiltonian that combines features of both Dirac and Schrödinger equations. The pseudospin changes its color index four times as it moves among four carbon sublattices (*2*–*4*).

A. K. Geim, Science, 2009
doi:10.1126/science.1158877

Graphene Band Structure



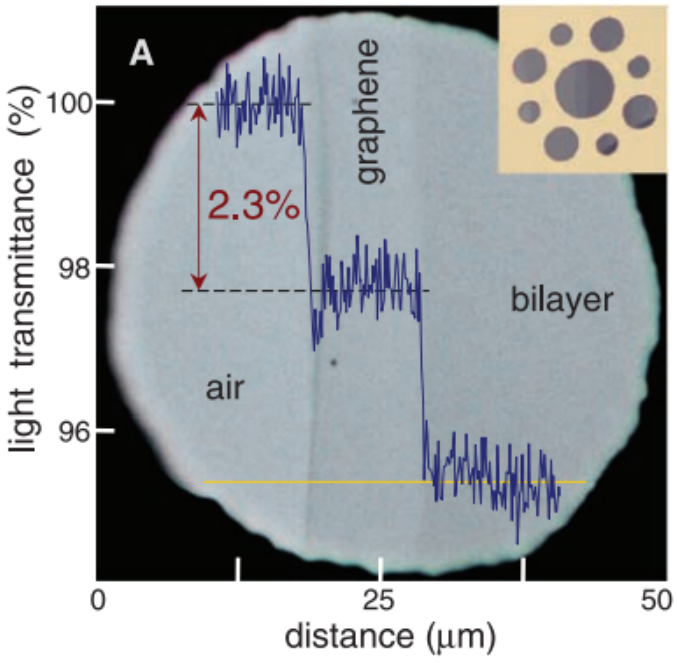
Effectively **doping with electric field**: Ambipolar electric field effect in single layer graphene.

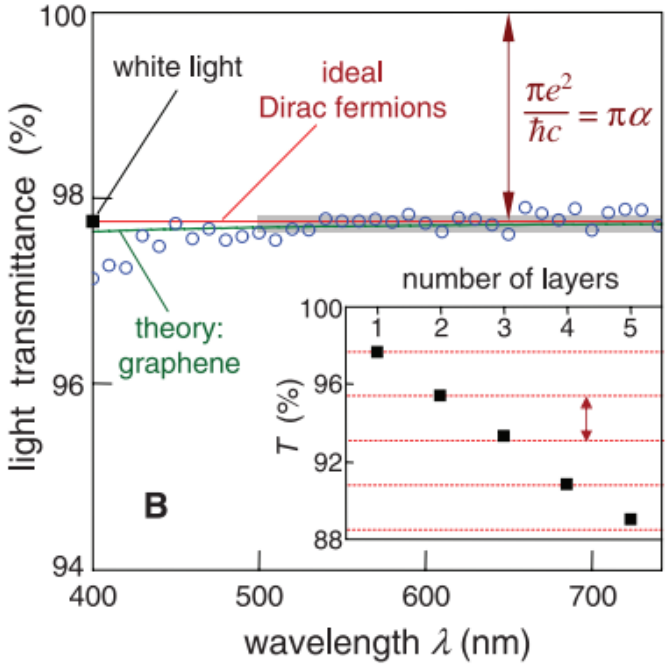
Figure 3 Ambipolar electric field effect in single-layer graphene. The insets show its conical low-energy spectrum $E(k)$, indicating changes in the position of the Fermi energy E_F with changing gate voltage V_g. Positive (negative) V_g induce electrons (holes) in concentrations $n = \alpha V_g$ where the coefficient $\alpha = 7.2 \times 10^{10}$ cm^{-2} V^{-1} for field-effect devices with a 300 nm SiO_2 layer used as a dielectric[7–9]. The rapid decrease in resistivity ρ on adding charge carriers indicates their high mobility (in this case, $\mu \approx 5{,}000$ cm^2 V^{-1} s^{-1} and does not noticeably change with increasing temperature to 300 K).

A. K. Geim, K. S. Novoselov, Nature, 2007
doi:10.1038/nmat1849

Properties of Graphene

"Fine Structure Constant Defines Visual Transparency of Graphene"





$T=(1+2\pi G/c)^{-2}$
$=(1+(1/2)\pi\alpha)^{-2}$

$R=(1/4)\pi^2\alpha^2 T$

Opacity
$(1-T) \approx \pi\alpha \approx 2.3\%$

"Instead of material parameters, absorption in graphene is determined by fundamental constants. […] **Coupling between light and relativistic electrons** and that is traditionally associated with quantum electrodynamics rather than materials science. "

R. R: Nair et al., Science, 2008
doi:10.1126/science.1156965

Properties of Graphene

"Electric Field Effect in Atomically Thin Carbon Films"

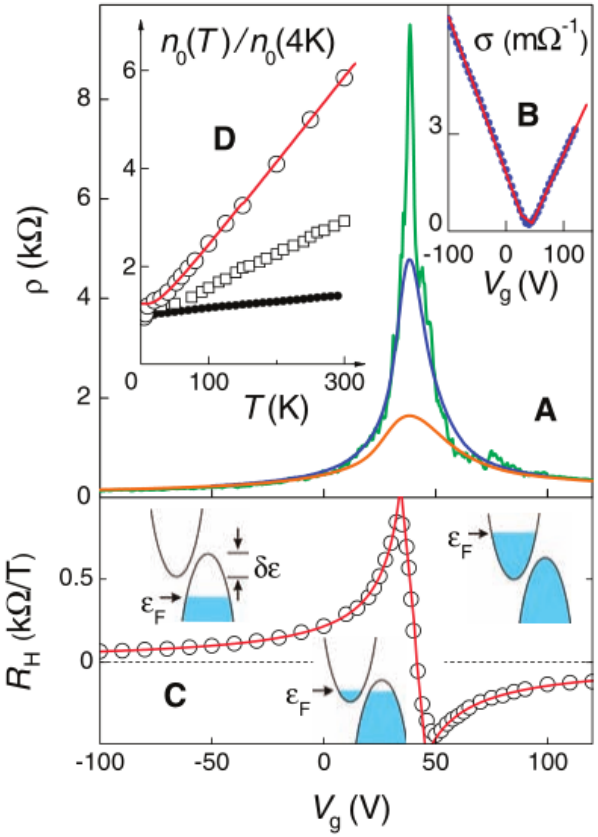


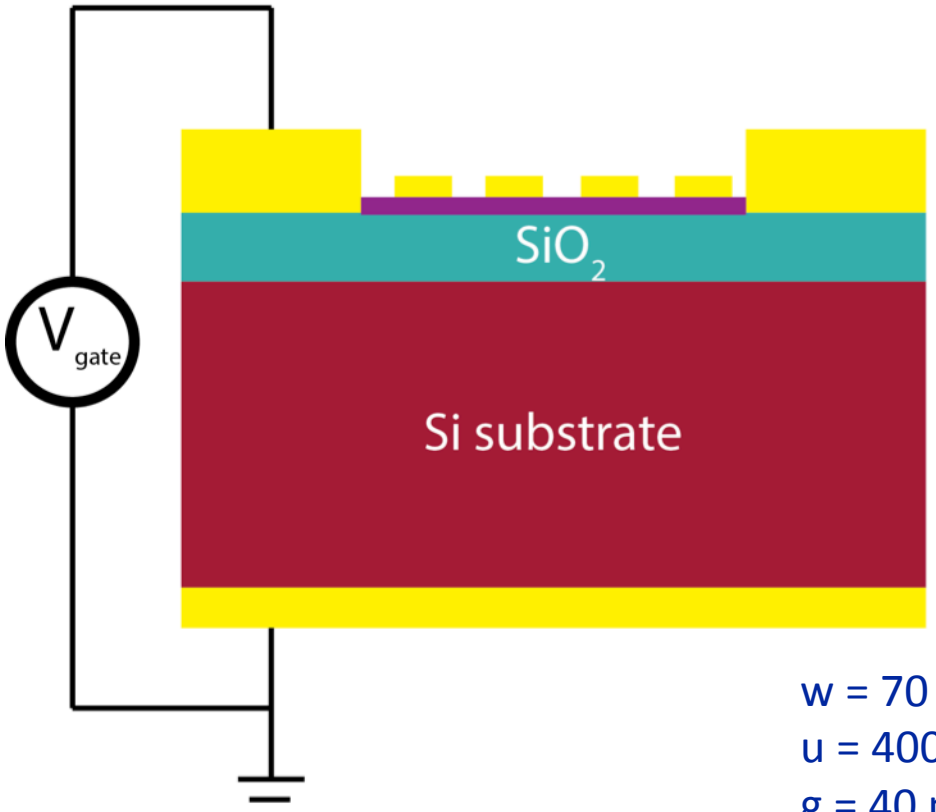
Fig. 2. Field effect in FLG. (**A**) Typical dependences of FLG's resistivity ρ on gate voltage for different temperatures (T = 5, 70, and 300 K for top to bottom curves, respectively). (**B**) Example of changes in the film's conductivity $\sigma = 1/\rho(V_g)$ obtained by inverting the 70 K curve (dots). (**C**) Hall coefficient R_H versus V_g for the same film; T = 5 K. (**D**) Temperature dependence of carrier concentration n_0 in the mixed state for the film in (A) (open circles), a thicker FLG film (squares), and multilayer graphene ($d \approx 5$ nm; solid circles). Red curves in (B) to (D) are the dependences calculated from our model of a 2D semimetal illustrated by insets in (C).

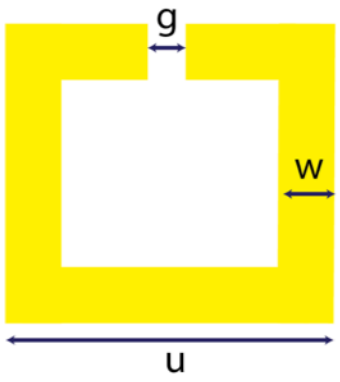
Effect of electric field in Few-Layer-Graphene

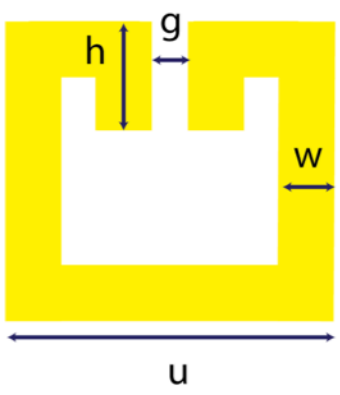
Conductivity tuning with Electric field

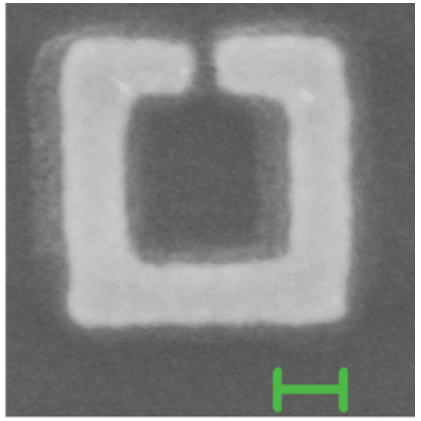
K. S. Novoselov, et al, Science, 2004
doi:10.1126/science.1102896

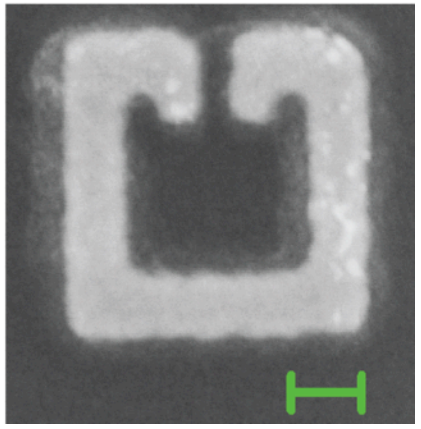
SRRs on back-gated graphene devices for coupling enhancement











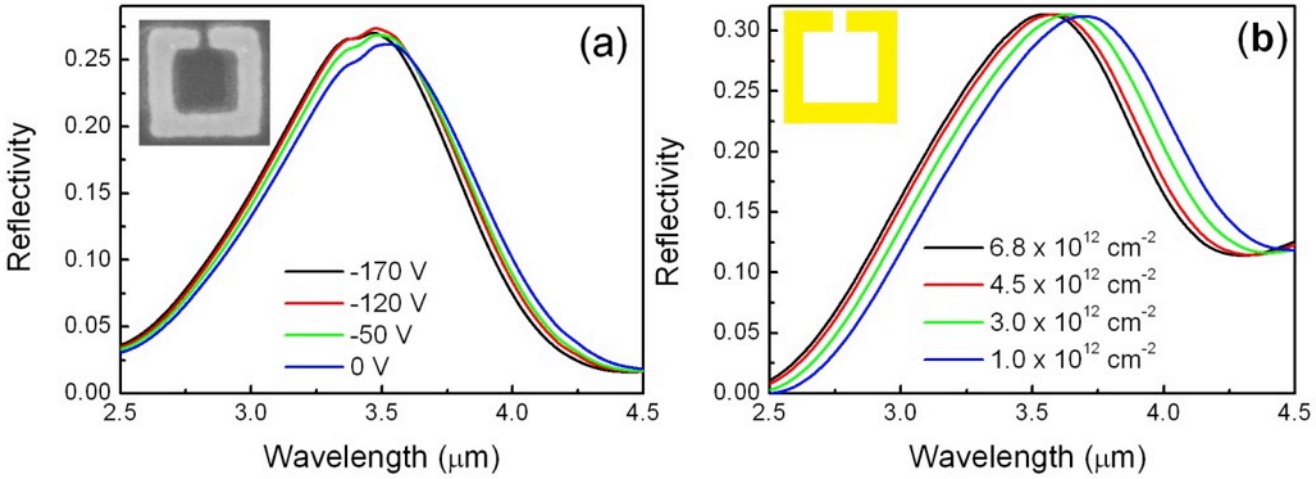
w = 70 nm
u = 400 nm
g = 40 nm
h = 120 nm

Scale bar is 100 nm.

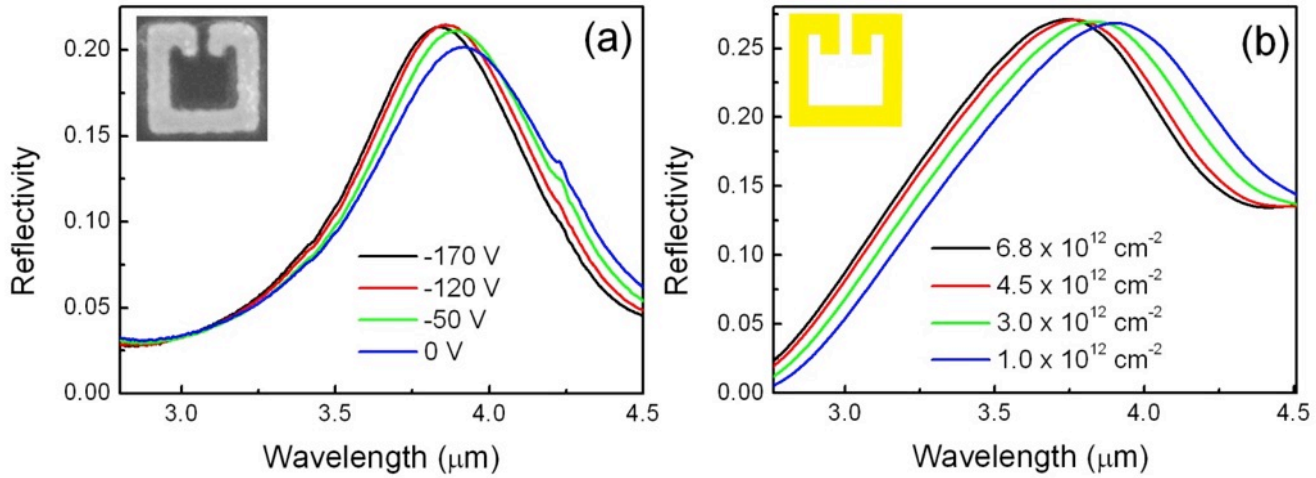
S. Cakmakyapan, H. Caglayan, and E. Ozbay. Carbon 80 (2014).

Reflectivity measurements and numerical calculations

62 nm shift



95nm shift



Acknowledgements

To all the founding fathers/ mothers of quantum mechanics who made our ongoing research possible

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