Magnetic Photonic Crystal Structures based on confined ferromagnetic doped II-IV-V_2 nanocomposites and heterostructures

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- Introduction - Motivation
- Ferromagnetism and Birefringence in II-VI-V_2 Chalcopyrites
  Materials properties/consideration
- Confined heterostructures and embedded nanocomposites
- Thin film materials development / optimization
- Nonlinear opto-electronic / magneto-optic device structures.

Multifunctionality: - the attraction of II-IV-V_2 compound semiconductors heterostructures!

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Confined (optical and/or electrical) structures based on birefringent chalcopyrite (CP) heterotructures and/or embedded ferromagnetic CP materials offer unique advantages:

- birefringent nature and the lower crystal symmetry in CP semiconductors allow for instance three-wave nonlinear parametric processes (the second-order nonlinearity) with very high values of the second-order hyperpolarizabilities;
- *recent discovery of RT ferromagnetism in diluted magnetic CP semiconductors (Mn, Fe, Co, V, Cr, or Ni) allows the construction of novel magneto-optical device structures based on ferromagnetic* $(II_{1-x}Mn_x)$*-IV-*V_2 *;*
- II-IV-V_2 CP compound semiconductors are compatible with III-V compound semiconductors, which opens new opportunities in exploring ferromagnetic nanocomposites and heterostructures.

Such structures are the basic elements for advanced nonlinear magneto-optical device structures, such as “magnetic photonic crystals” (MPC). Potential applications include compact ultra-sensitive sensors, nonlinear optical modulators, QD lasers, magneto-optical switches, detectors, and spin electronic devices.

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Potential of confined birefringent / ferromagnetic II-IV-V_2 Chalcopyrite (CP) nanocomposites and heterostructures

Development of confined birefringent & ferromagnetic II-VI-V_2 CP structures

OPO applications

1D and 2D confined layers for frequency agile laser light generation in the near- and far IR wavelength range.

Vertical and lateral confined device structures for sum- and difference frequency mixing

Integrate solid state pump laser
1 - 2.7 µm output

Sensitization of probe surface / interface to specific molecules

Integrated Solid State Molecular Sensors (SSMS*)

SHG applications (thick layers)

Use of high power CO_2 laser (10.6 µm)

- SHG (5.3 µm)
- FHG (2.7 µm)

Chemical Gas Sensors

Air Quality Monitoring

Counter Measure

Photonic and Magnetic Photonic crystals *(confined nanocomposites)*

2D & 3D ferromagnetic and/or birefringent CP nanocomposites and heterostructures embedded in confined (optical / electrical) cladding layers

- All Photonic switches
- Spintronic devices
- Optical communication devices
- Laser light protection devices

* N. Dietz and K.J. Bachmann, US Patent Number 6,442,319, Aug. 27, 2002.

What is Spintronics?

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Electronics: based on movement of electronic charge

Spintronics: based on spin property of electrons

Devices use spin exclusively or in addition to charge, which provides advantages over conventional electronics

- increased functionalities
- decreased power consumption
- non-volatility

Characteristics of Spin:

- Fundamental quantum property
- Defined as the intrinsic angular momentum of an elementary particle
- Has two states classified as up or down
- Can be manipulated by externally applied magnetic fields
- Has a long coherence time

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Potential Applications

Giant magnteo-resistance (GMR)

Ferromagnetics - long lasting memory storage

Electronics - added functionalities

- Multistate and Reconfigurable Logic
- Ultra-Fast Logic Functions

Photonics - circularly polarized light related to spin

- spin-LEDs produce polarized light
- can be used to measure degree of spin
- ultra-fast lasers can maintain and amplify spin-coherence

Novel Magneto-electro-optical devices

Materials for Spintronics

- Ferromagnetic/Superconductor
- Ferromagnetic metals - Fe
  - Anisotropic magnetoresistance (~1%)
- Paramagnetic Semiconductor - (Be)ZnMnSe
- Ferromagnetic Semiconductors
  - ➢ (Ga: Fr)As
  - ➢ (Ga:Fr)N and (In:Fr)N
  - ➢ *(II:Fr)-IV-V_2 Chalcopyrite compounds*

Fr denotes magnetic elements such as, Mn, Fe, Co, V, Cr, or Ni

Giant Magneto-Resistive (GMR) read heads

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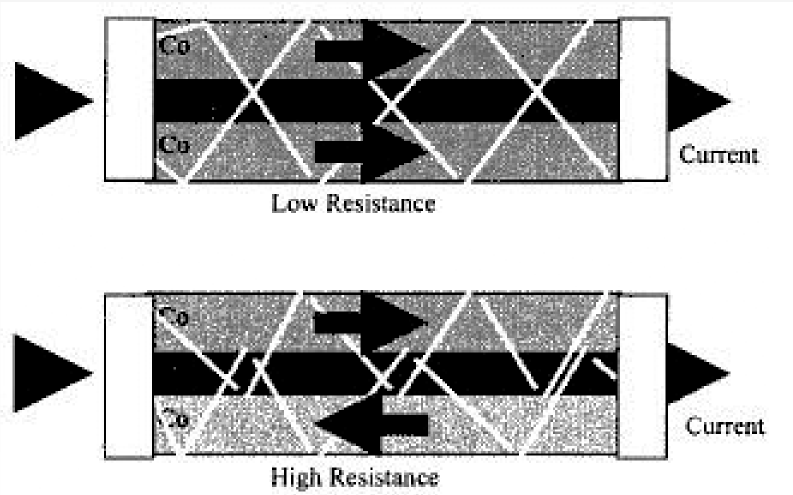
Elementary spintronic application (spins act in passive manner)

Very high performance disk drives utilize GMR

Consist of alternating ferromagnetic and nonmagnetic layers

Resistance controlled by relative orientation of magnetic layers



- Alignment of moments correspond to low resistance
- Anti-alignment of moments in alternate layers result in higher resistance

S.A Wolf, D. Treger, "Spintronics" *Magnetics, IEEE Transactions on* , vol. 36, p.2748 (2000)

GMR device consists of a three-layer sandwich of a magnetic metal such as cobalt with a nonmagnetic metal filling such as silver. A current passes through the layers consisting of spin-up and spin-down electrons. Those oriented in the same direction as the electron spins in a magnetic layer pass through quite easily while those oriented in the opposite direction are scattered. If the orientation of one of the magnetic layers can easily be changed by the presence of a magnetic field then the device will act as a filter, or 'spin valve', letting through more electrons.

Magnetic Random Access Memory (MRAM)

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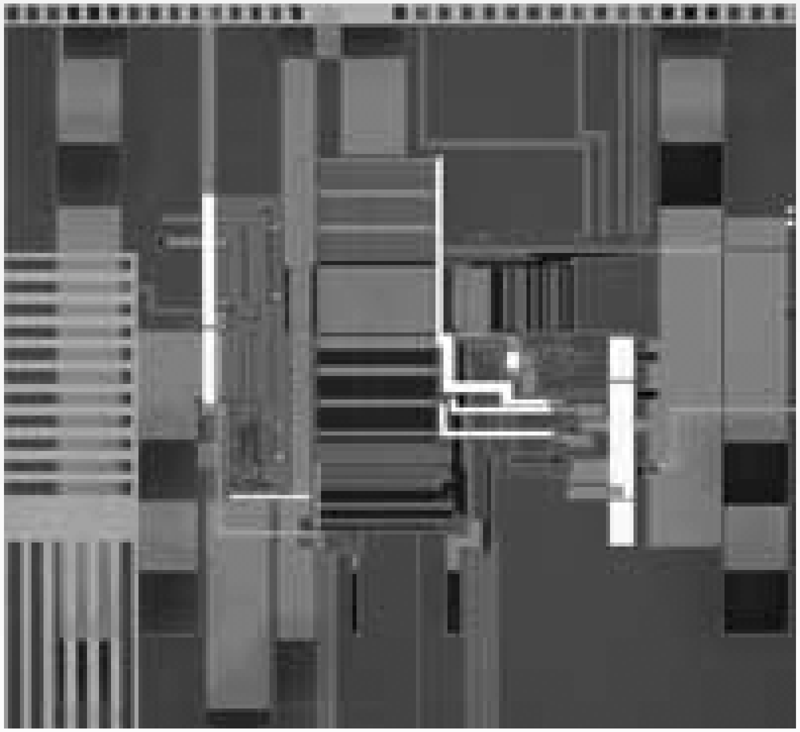

IBM's spin-based M-RAM chip stores data without drawing power.

Spin valves can also be made to act as switches by flipping the magnetisation in one of the layers. This allows information to be stored as 0s and 1s (magnetisations of the layers parallel or antiparallel) as in a conventional transistor memory device. The advantage of magnetic random access memory (MRAM) is that it is 'non-volatile' - information isn't lost when the system is switched off. MRAM devices would be smaller, faster, cheaper, use less power and would be much more robust in extreme conditions such as high temperature, or high-level radiation or interference.

Spin Sources - Ferromagnetic vs. Semiconductor

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Ferromagnetic materials (Fe)

- Injected electrons are spin-aligned
- Source in contact with semiconductor interface
- Electrons lose polarization quickly after leaving source

Semiconductor materials (GaAs)

- Electric field, external or built in, carries electrons from source
- Amplification, spin injection, spin filters, etc.
- Polarized light creates spin-polarized pools of electrons
- Integration into existing electronics

However spin polarization usually occurs only at cryogenic temperatures

Current Issues for Semiconductor Based Spintronic Devices

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Requirements to make Spintronic devices feasible:

- *Stable source of spin-polarized carriers*
- *Mobile Spins transferred efficiently*
  - across interfaces of different semiconductor materials
  - without appreciable loss in spin polarization
- *Polarization maintained long enough to operate on*
- *Operating temperatures > T_{RT} (300K)*

II-VI Semiconductors:

Independent tailoring of electronic and magnetic properties

- *Strong exchange and Coulomb interaction / Pronounced exciton-photon coupling*
- *Integration of transition metals with half-filled 3d-shell (Mn) isoelectronically in crystal matrix*

Spin injection into semiconductors has been demonstrated / Ferromagnetic phase transition observed

III-V Semiconductors:

- Relatively high Curie temperatures (T_c=110K for (Ga:MnN); Hole induced ferromagnetism
- Photo-carrier-induced magnetic transitions at relatively low carrier concentrations
- Epitaxially grown within non-magnetic semiconducting heterostructures
- Integration into existing electronics and optoelectronics

Datta-Das Spin Transistor

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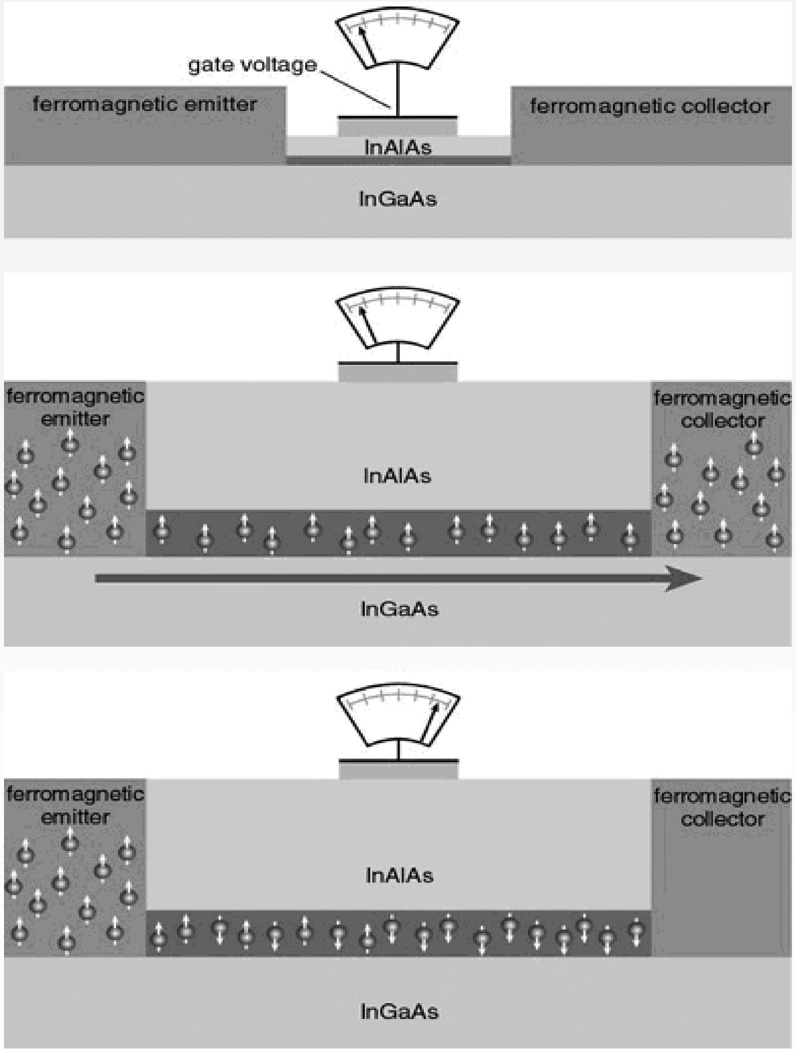
- Typical spintronic device concept
- First spintronic device based on MOS technology
- Spin-aligned electrons are emitted into a narrow channel
- Gate off - aligned spins pass through channel
- Gate on - spins precess and cannot pass into collector

<u>Has yet to be convincingly demonstrated</u>



"Spintronics" American Scientist, vol. 89, p. 516 (2001)

Zener Model: Dietl *at al.* Science 287 (2000) 1019

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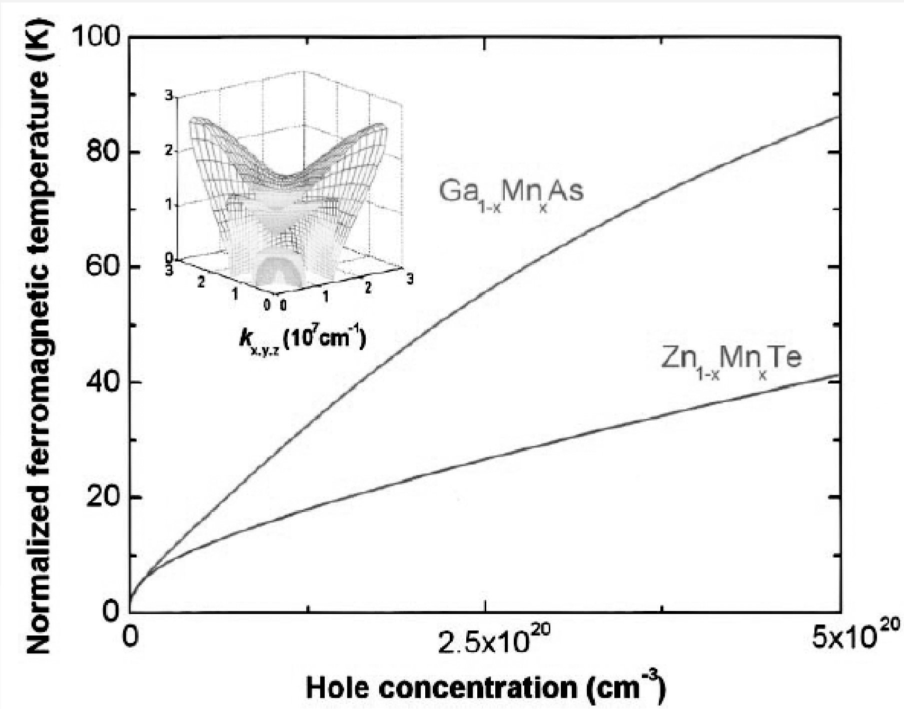
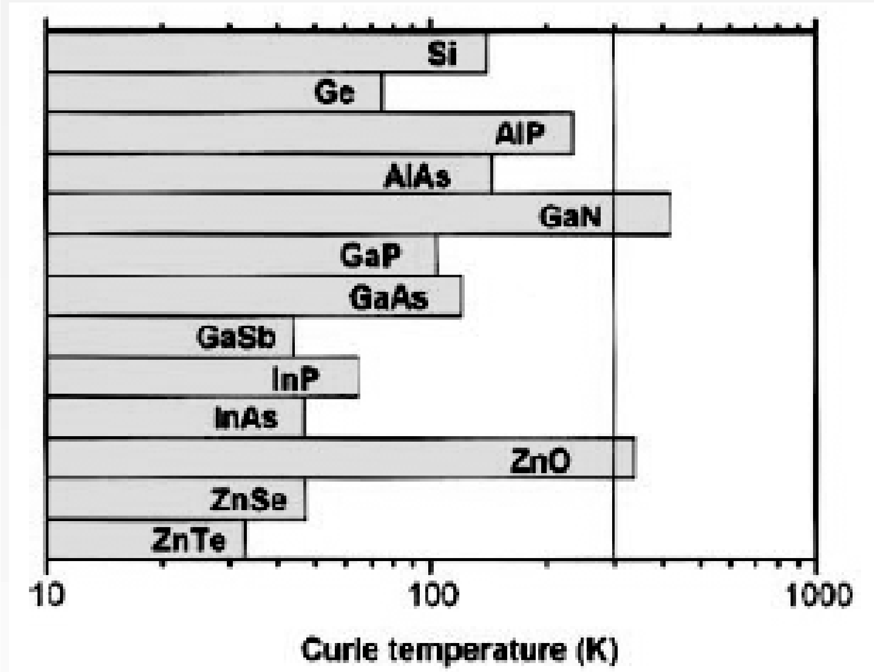


Normalized ferromagnetic temperature T_F^{nor} as a function of hole concentration. The complex valence-band structure (insert) was used to determine the mean-field values of T_F^{nor} for p-GaAs and p-ZnTe containing 5% Mn.



Computed values of the Curie temperature T_C for various p-type semiconductors containing 5% of Mn and 3.5x10^{20} holes per cm^3.

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(Ga:Mn)N

- High quality GaMnN still has not been produced
- The possibility for room temperature ferromagnetism is high
- MOCVD technique of choice for growing GaN based materials
- Possibility for investigating optically active devices

Issues for MOCVD growth

Are chemistries compatible with current GaN growth available?

Will the Mn (or Fe) incorporate substitutionally?

Will the Mn segregation and form precipitates?

Can high p-doping be obtained at the levels required?

Will high background doping of GaN result in compensated material?

Ferromagnetism in II-IV-V_2 Chalcopyrites

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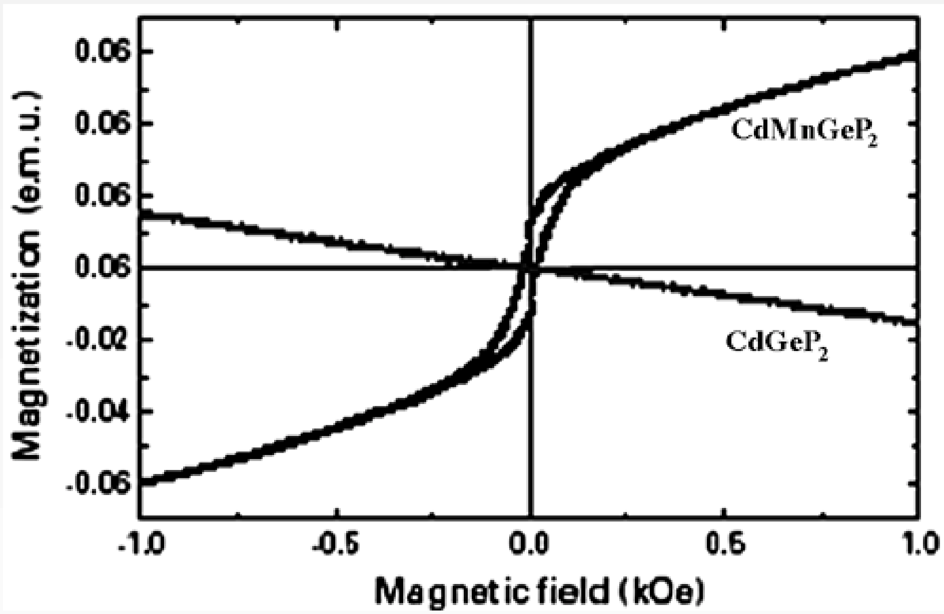
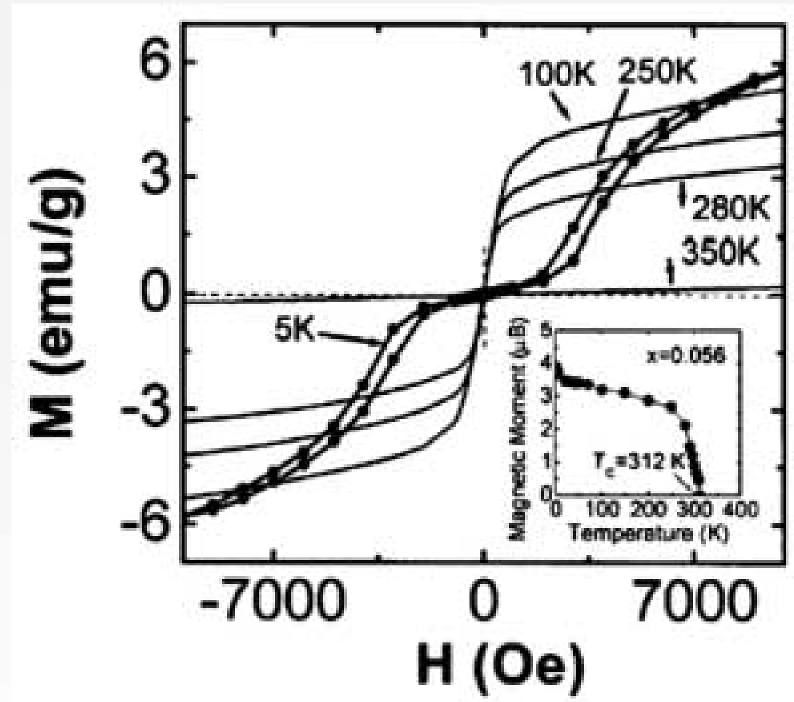
K. Sato, G. Medvedkin and T. Ishibashi, J. Cryst. Growth **237-239**, 1363 (2002).



Magnetization of polycrystalline undoped $CdGeP_2$ and $(Cd:Mn)GeP_2$ at 298 K annealed at T=500K for 30 min.

S. Cho et al., Phys. Rev. Lett. **88**, 257203 (2002).



Temperature dependent magnetization of polycrystalline $(Zn_{0.944}Mn_{0.056})GeP_2$.

- Mn doping/alloying through solid state diffusion from crystal surface into bulk region (annealing);
- Mn incorporation as high as 20% demonstrated;
- Mn can be substitute readily for group II (Cd, Zn, Sn) cations without forming structural defects;
- Ferromagnetic thin film heterostructures have not been reported yet.

Ferromagnetic (II:Fr)-IV-V_2 nanocomposites

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- Ferromagnetic (II:Fr)-IV-V_2 nanocomopsites have not been produced
- ***The possibility for room temperature ferromagnetic device structure is high***
- ***Lattice-matched substrates are not required***
- OMCVD and vapor phase diffusive/reactive conversion (VPDRC) techniques are the choice for fabrication of (II:Fr)-IV-V_2 nanocomposites

Issues for OMCVD growth

Are chemistries compatible with II-VI-V_2 growth parameter?

Lattice strain as control parameter for nanocomposite size & spatial distribution?

Will the Mn incorporate substitutionally with group II cations?

Will the Mn segregation and form precipitates/clusters?

Can n- or p-doping be obtained at the levels required?

Will high background doping result in compensated material?

Confined ferromagnetic II-IV-V_2 nanocomposites

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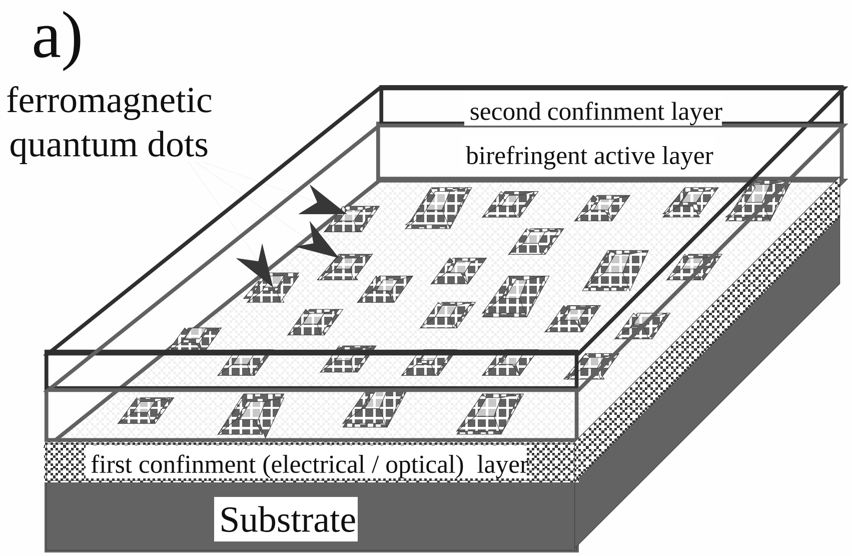
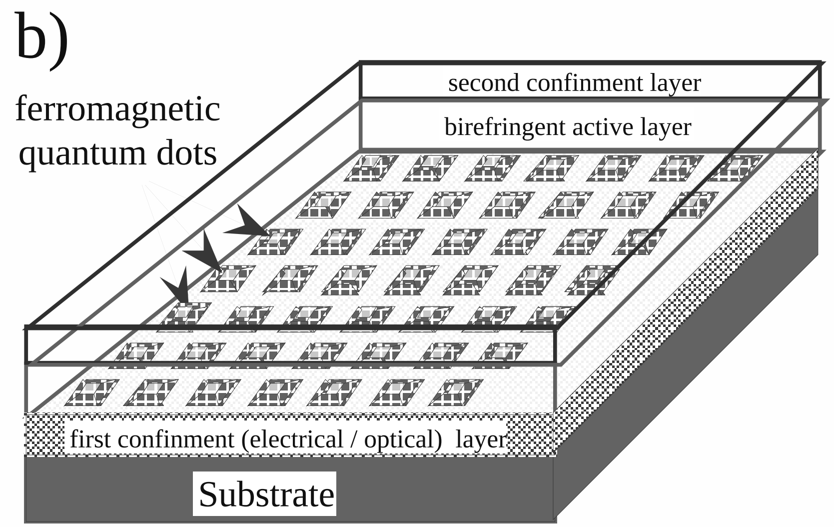


Self-assembled magnetic quantum dots embedded in a birefringent layer.



Magnetic Photonic Crystal (MPC)

built up by size and distribution engineered period assemblies of magnetic quantum dots embedded in a birefringent layer.

Confined ferromagnetic II-IV-V_2 nanocomposites in birefringent II-IV-V_2 layers

- Confined Ferromagnetic (II:Fr)-IV-V_2 nanocomopsites have not been produced
- ***Lattice-matched substrates are required***
- OMCVD and LPE in conjunction with vapor phase diffusive/reactive conversion (VPDRC) are the choice for fabrication of confined nanocomposites

Additional issues for confined II-IV-V_2 nanocomposites growth

What are best suited lattice-matched II-IV-V_2 / III-V or II-VI systems

What are the best control parameter for nanocomposite size & distribution?

Can we obtain sharp interfaces between heterostructures (interdiffusion)?

Can n- or p-doping in the layers obtained at the levels required?

Does Mn incorporation affect the birefringence of II-IV-V_2

II-IV-P_2/As_2 material systems of interest

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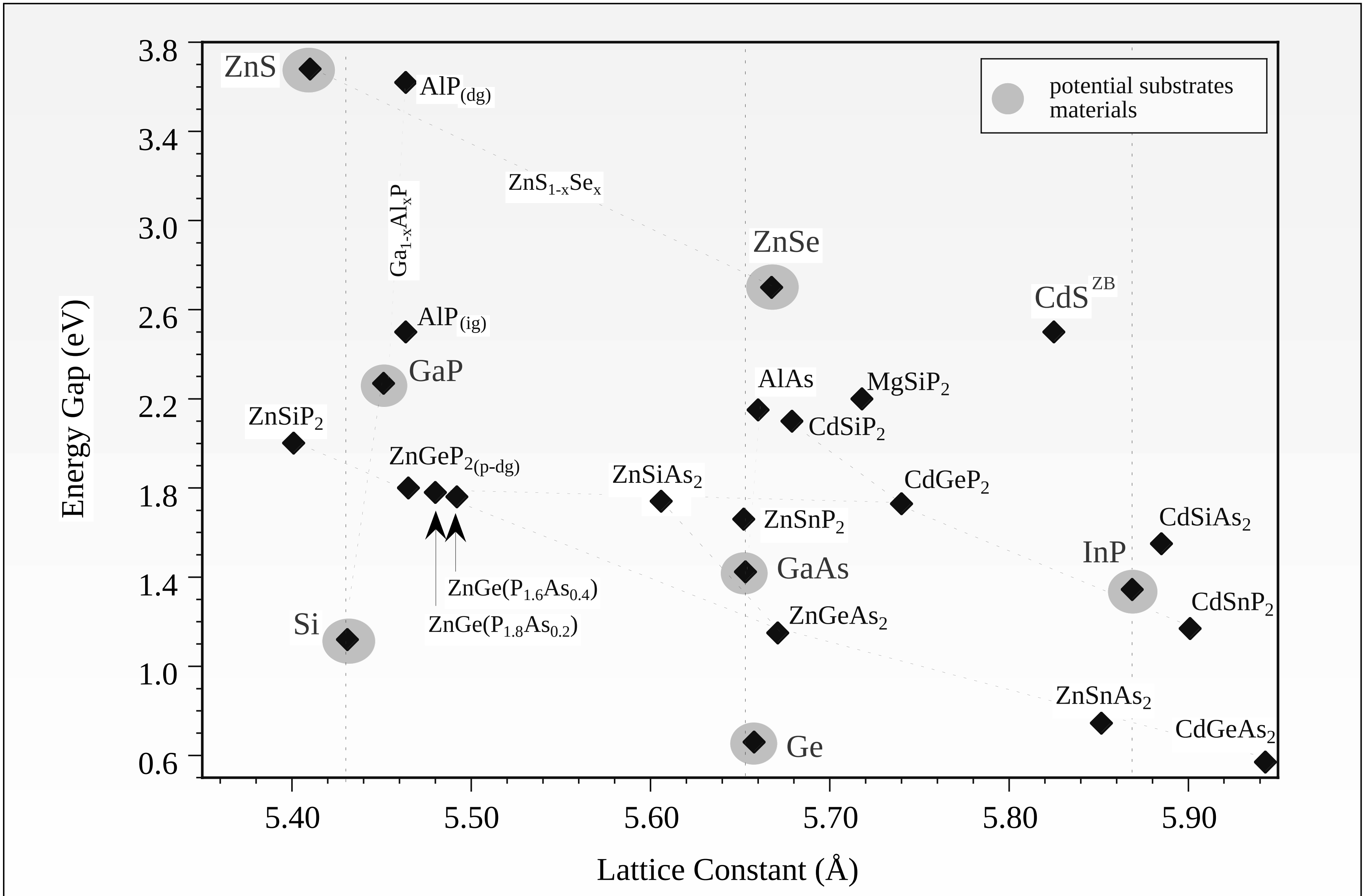

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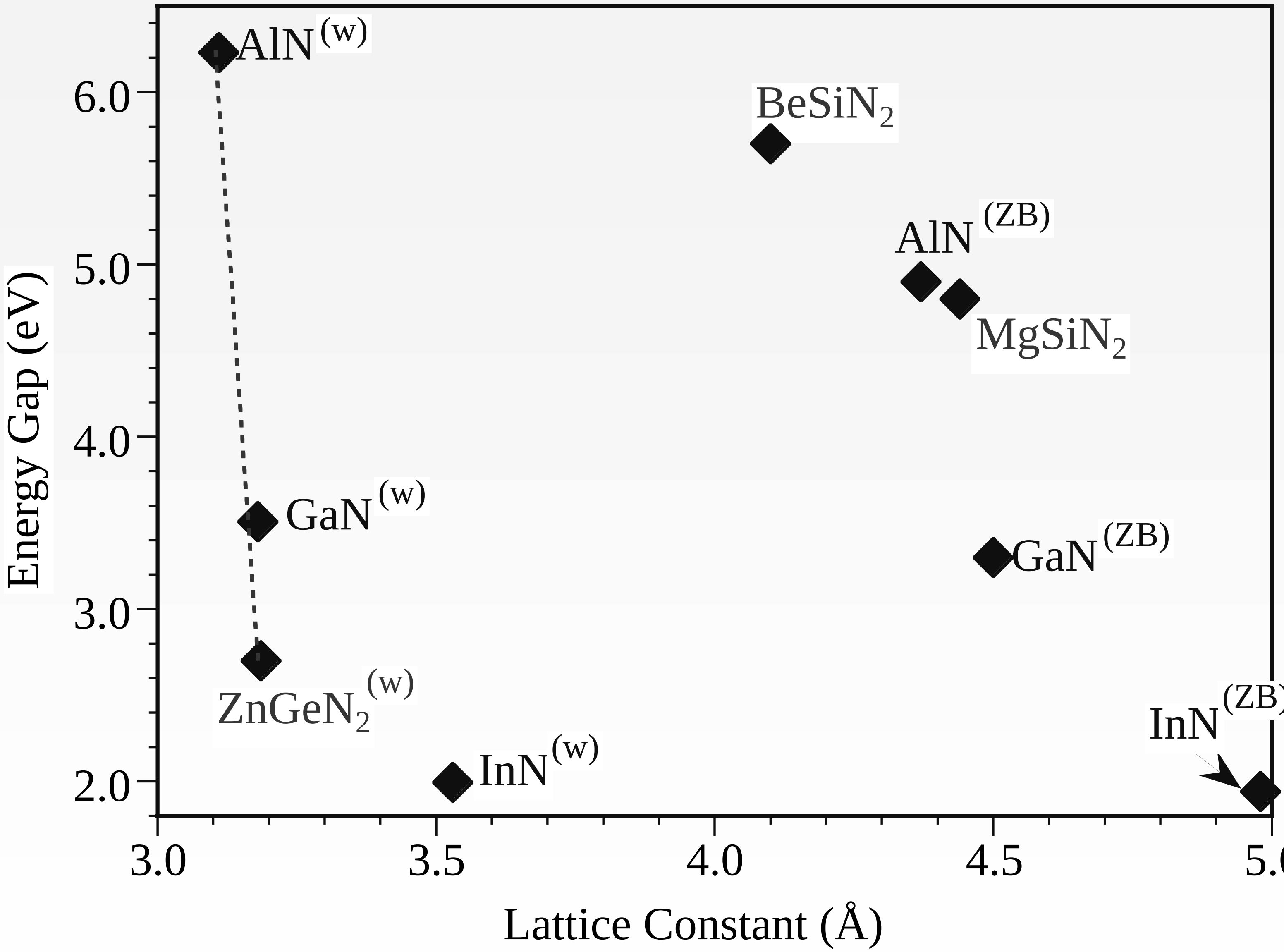
II-IV-N_2 material systems of interest



Optical confined birefringent II-IV-P_2 heterostructures

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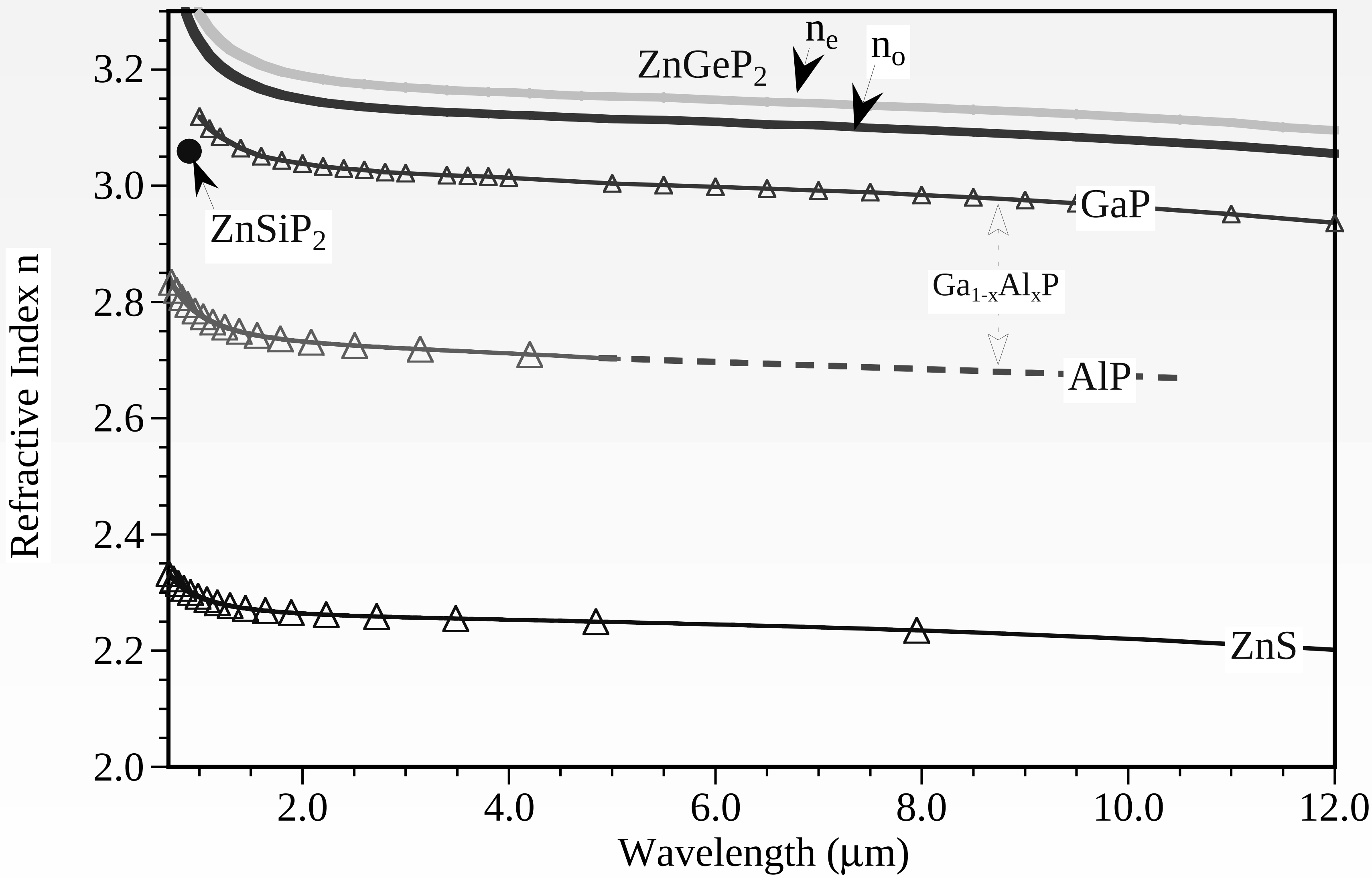

Optical confined birefringent II-IV-As_2 heterostructures

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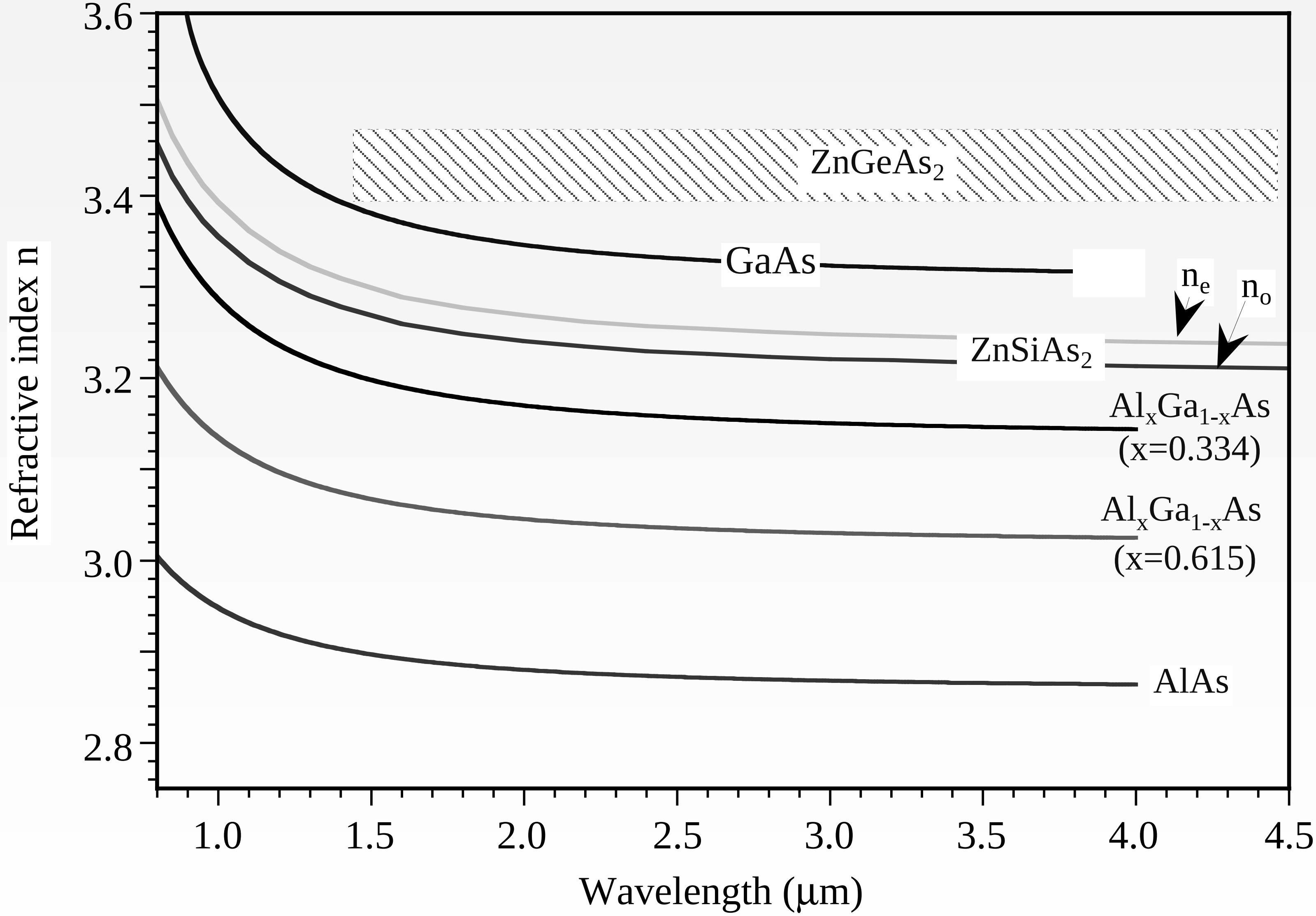

Potential confined birefringent II-IV-V_2 system

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II-IV- phosphide systems

	Active birefringent layer	Lattice-matched substrates	Confinement layers
(a)	$Zn(Ge_{1-x}Si_x)P_2$	GaP and Si	$Ga_{1-x}Al_xP$
(b)	$(Cd_{1-x}Zn_x)$ Ge P_2	GaAs, ZnSe	$Ga_{1-x}Al_xAs$
(c)	$(Cd_{1-x}Mg_x)SiP_2$	GaAs, ZnSe	$Ga_{1-x}Al_xAs$
(d)	$ZnSnP_2$	GaAs, ZnSe	$Ga_{1-x}Al_xAs$
(e)	$Cd(Ge_{1-x}Sn_x)P_2$	InP	CdS

II-IV- arenide systems

	Active birefringent layer	Lattice-matched substrates	Confinement layers
(a)	$Zn(Ge_{1-x}Si_x)As_2$	GaAs, ZnSe	$Ga_{1-x}Al_xAs$
(b)	$(Cd_{1-x}Zn_x)$ Ge As_2	InP	CdS
(c)	$ZnSnAs_2$	InP	CdS
(d)	$CdSiP_2$	InP	CdS

II-IV- nitride systems

	Active birefringent layer	*Lattice-matched substrates*	*Confinement system*
(a)	$Zn(Ge_{1-x}Si_x)N_2$	*wurtzite* GaN, SiC, Sapphire	*$Ga_{1-x}Al_xN$,*
(b)	*([Zn or Mg or Be)SiN_2*	*zincblende $Ga_{1-x}Al_xN$, InN*	

Phase-Matched Nonlinear Optics in Birefringent Materials

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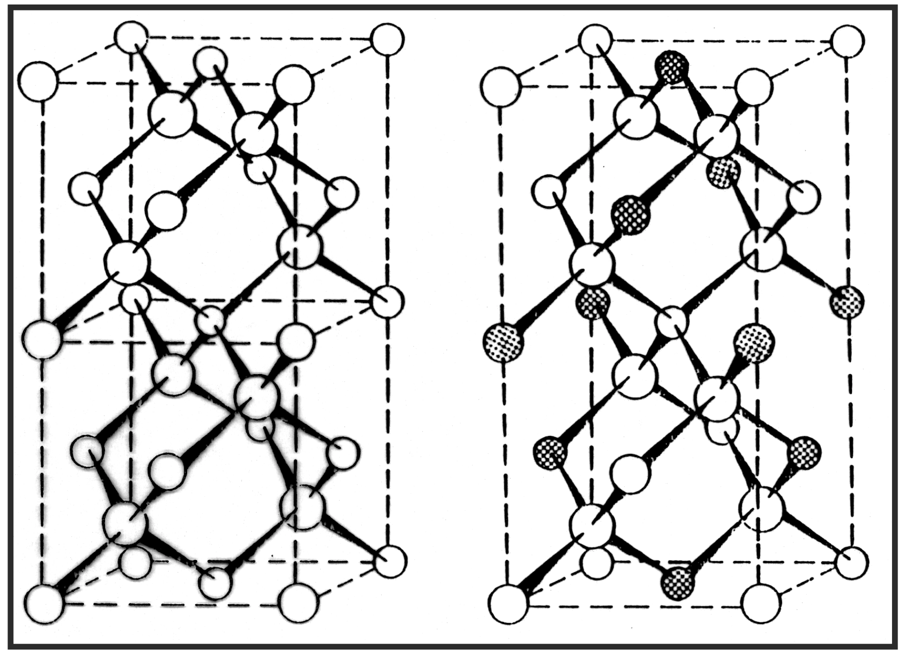
- Phase-matched ordinary and extraordinary beam combinations permit efficient sum- or difference-frequency mixing, harmonic generation, and generation of tunable laser radiation by optical parametric oscillators

IB	IIB	IIIB	IVB	VB	VIB
		13 Al	14 Si	15 P	16 S
29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se
47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te



Ordered substitution of atom positions in the fcc sublattices of diamond-structure

- zincblende structure III-V and II-VI compounds
- chalcopyrite structure II-IV-V_2 and I-III-VI_2 compounds
- adamantine structure materials