RECENT RESEARCH ACTIVITIES IN AKR GROUP

General area of research:

Experimental Condensed Matter Physics, Materials Physics, Nanosciences and Nanotechnology

Current areas of interest :

a) Nanoscience and nanotechnology particularly fabrication of single nanowires devices using nanolithography tools and physical experiments on single nanowires probing physics of size reduction in phenomenon like localization, metal – insulator transition, charge ordering, Ferro and Anti-ferromagnetic transition and Charge Density wave transition.

b) Opto-electronic properties and resistive state switching in charge transfer complex nanowires like Cu-TCNQ nanowires.

c) Opto-electronic properties of Si and Ge nanowires for detector applications.

d) Physics of correlated transition metal oxides particularly perovskite oxides including electrical, magneto-transport and magnetic properties (like manganites that show colossal magneto-resistance, Vanadium oxides and nickelates that show temperature driven metal insulator transition) .Tuning transition by strain and charge created by Electric Double Layer (EDL) gate dielectric .Application of noise spectroscopy (1/f noise and Nyquist Noise) to investigate metal-insulator transition.

e) Opto-electronic properties of wide band gap semiconductor like ZnO and engineering their properties by Electric Double Layer (EDL) gate dielectric.

Some of the past areas worked on:

a) Low energy excitation in glasses (TLS) and physics of glassy state.

Representative publications **:**
(Raychaudhuri and Pohl, Phys. Rev. **B25**, 1310 (1982), Raychaudhuri and Hunklinger Z. Phys. **B57**, 113 (1984), Hunklinger and Raychaudhuri *PROGRESS IN LOW TEMPERATURE PHYSICS. Vol. IX* page 265 (1986) , Raychaudhuri and Hasegawa **”** Phys. Rev. **B21**, 479 (1980), Mukhopadhyay and .Raychaudhuri , J. Appl. Phys. **67,** 5235 (1990) , Rajeswari and Raychaudhuri , Phys.Rev. **B 47,** 3036 (1993)

b) High temperature superconductor.

Representative publications **:**

Rao,Ganguly,Raychaudhuri and Mohanram, Nature. **326,** 856 (1987), .Srikanth and Raychaudhuri **"**Phys.Rev. **B 45,** 383 (1991-II) , Srikanth and .Raychaudhuri ,Physica **C190,** 229 (1992)

c) Metal insulator transition in transition metal oxides.

Representative publications **:**

, **"Low temperature elecronic properties of a normal conducting perovskite oxide ($LaNiO_3$)"** Solid State Comm. **79,** 591 (1991)

"Low temperature conductivity of Ta compensated sodium bronze near the metal-insulator transition" Phys.Rev. **B 44,** 8572 (1991-II)

"Quantum corrections to conductivity in a perovskite oxide : A low temperature study of $La\ Ni_{1-x}\ Co_x\ O_3$" Phys. Rev. B 46, 1309 (1992).

"Metal – Insulator Transition In perovskite oxides : Tunneling Experiments" Phys. Rev **B 51**, 7421 (1995)

"**Metal-insulator transition in perovskite oxides: a low temperature perspective**" Advances in Physics 44, 21 (1995)

"**Electronic conduction in $LaNiO_{3-\delta}$: Dependence on oxygen stoichiometry**",J. Phys: Condens. Matter **10,** 1323 (1998)

(1998) " Disorder effects in electronic structure of substituted transition metal compounds"
Phys. Rev. Letts **80,** 4004

d) Colossal Magnetoresistance (CMR) and Charge ordering in hole doped rare earth oxides.

Representative publications **:**

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(1996) "**Structure electron- transport properties and giant magnetoresistance of hole doped $LaMnO_3$ systems."** Phys. Rev **B 53,** 3348

(1996) "Effect of particle size on the giant magnetoresistance of $La_{0.7}\ Ca_{0.3}\ MnO_3$" Appl. Phys. Letts. **68,** 2291

(1996) "Magnetoresistance of the spin state transition compound $La_{1-x}Sr_xCoO_3$"
Phys. Rev **B 54,** 16 044

(1996) "Thermopower and nature of the hole doped states in $LaMnO_3$ and related systems" Phys. Rev. B (Rapid Commn) **54,** R 9604

(1996) "Low temperature specific heat of $La_{0.67}Ba_{0.33}MnO_3$ and $La_{0.8}Ca_{0.2}MnO_3$ "
Phys. . Rev.B, **54,** 14 926

(1996) "Structural changes and related effects due to charge ordering in $Nd_{0.5}Ca_{0.5}MnO_3$
Phys. Rev **B 54,** 15 303

(1998)" Incipient charge order in a mangante with a critical average radius of the A-site cation " Phys. Rev. (Rapid commn.) **57,** R 8115.

(1999) " The density of states of hole-doped manganites : A scanning tunneling microscopy/spectroscopy study" , Phys. Rev. **B 59** , 5368

(2000) "Collapse of charge ordering gap of $Nd_{0.5}Sr_{0.5}MnO_3$ in an applied magnetic field" J.Phys. Condens. Matter (letters) **12**, L 101

(2000)"Magnetic field resulting from non-linear electrical transport in single crystals of charge –ordered $Pr_{0.63}Ca_{0.37}MnO_3$ " Phys. Rev **B62,** (Rapid Comm) R11941

(2001)"Specific Study study of Single crystalline $Pr_{0.63}Ca_{0.37}Mn0_3$ in presence of a magnetic field" , Phys. Rev **B64,** 165111

(2003) " Low frequency random telegraphic noise (RTN) and 1/f noise in rare-earth manganite $Pr_{0.63}Ca_{0.37}MnO_3$ near the charge ordering transition",
Phys Rev**. B 67** , 174415

(2003) "Effect of strain and microstructure on the electrical conduction in epitaxial films of $La_{0.7}Ca_{0.3}MnO_3$ ".,Phys Rev**. B 67** , 214415

(2003)" Depletion of density of states at the Fermi level in metallic colossal magnetoresistive Manganites" Phys Rev **B 68,** 134428

(2005) "Temperature dependence of the density of states near Fermi level in a strain free epitaxial film of hole doped manganite $La_{0.7}Ca_{0.3}MnO_3$." Phys. Rev **B 71** , 094426

(2005)"Collapse of charge-ordering state at high magnetic fields in the rare-earth manganite $Pr_{0.67}Ca_{0.33}MnO_3$" Phys. Rev **B 71** , 024426

Some of the research problems currently pursued in AKR group

Nanomaterials: growth ,characterization and physics of size reduction:

In recent years the AKR group focused on the general areas of nanoscience and nanotechnology, particularly on measurements of single nanowires. The research activities in this area has strong overlap with the group of Dr.Barnali Ghosh (Saha) of our centre. Prof. AKR also collaborates with other colleagues of the centre and other institutions in the country and abroad.

A specific problem of size reduction is that it can affect cohesive energy and related properties like mechanical properties, melting point, Debye temperatures etc . It can also affect the electronic transport by even classical size effect.Our investigation is directed to understanding of how the basic thermodynamic properties get affected by size reduction. The size reduction through finite size effects also affects such phase transitions like ferromagnetic transitions and the critical behavior near the transition temperature.

"Engineering" properties of nanomaterials in a predetermined and controlled manner would need an understanding of ionic diffusion as well as creation and diffusion of defects. AKR group is trying to understand some of the basic issues involved in this process through controlled experiments on lithographically fabricated nanostructures.

Size reduction , in complex systems, can tune their ground state. In complex oxide nanowires and nanoparticles this can lead to very different transport and magnetic properties as compared to the bulk. Understanding the evolution of different electronic and magnetic phases and their dependence on the structure can be utilized to design the physical properties of nanomaterials using size as the control parameter.

Size reduction as in nanowires can also affect the noise and fluctuations significantly as the smaller size of the nanowires make them more prone to fluctuations. These noise can come form structural origin, electronic origin and also from spins which in nanowires are aligned by shape anisotropy but are prone to creation of domain walls by thermal fluctuations.

Some of the representative publications in this area

Area: Growth of nanomaterials :

(2004) "Oriented growth of nanowires in templates: Example of Lanthanum Strontium Manganese oxide in alumina templates" Nanotechnology **15**, 1312

(2005) "Fabrication of Nanowires of multicomponent oxides: Review of recent advances" Materials Science and Engineering **C 25,** 738-751

(2006) "Low temperature Polymer Precursor based Synthesis of Nanocrystalline particles of Lanthanum Calcium Manganese oxide ($La_{0.67}Ca_{0.33}MnO_3$) with Enhanced Ferromagnetic Transition Temperature" Journal of Materials Research **21**,27-33

(2006) "Structural and Optical properties of nanoparticles of $Zn_{1-x}Mg_xO$ grown by low temperature chemical route. J. Applied Physics 100, 034315

(2008) "**A novel method of synthesis of dense arrays of aligned single crystalline copper nanotubes using electrodeposition in presence of a rotating electric field"** Advanced . Mater. **20,** 149

(2011) "Fabrication and Magnetic anisotropy study of $La_{0.67}Ca_{0.33}MnO_3$ nanowires" J. Appl. Phys**. 109**, 07D720

<u>Area:Electronic transport in nanowires and thermodynamic aspects:</u>

(2006) "Temperature dependence of the resistance of metallic nanowires (diameter ≥15nm): Applicability of Bloch-Gruneisen theorem." Phys. Rev B **74**, 035426

(2009) "Low temperature electrical Transport in ferromagnetic Ni Nanowires". **.**Phys. Rev B **79**, 205417

(2010) " Resistance anomaly near phase transition in confined ferromagnetic nanowires". Physical Review B **82**, 195425

(2012) "Temperature dependent (3K≤ *T* ≤300K) electrical transport in Cu nanotubes grown in porous alumina templates." ". New J. of Physics **14** 043032.

(2013) "Link between depressions of melting temperature and Debye temperature in nanowires and its implication on Lindeman relation" JOURNAL OF APPLIED PHYSICS **114**, 224313

<u>Area: Tuning the ground state by size reduction</u>

(2004) "Synthesis of ordered array of nanowires of $La_{0.67}Ca_{0.33}MnO_3$ (x=0.33) in alumina templates with enhanced ferromagnetic transition temperature. Appl. Phys. Letts **, .84** 993

(2005) "Electronic transport in nanostructured films of $La_{0.67}$ $Sr_{0.33}MnO_3$" J.Appl.Phys, **98**, 094302

(2008) "Crystal structure and physical properties of half-doped manganite nanocrystals with size < 100nm". Phys. Rev B **77**, 235112

(2012) "Electrical transport properties of nanostructured ferromagnetic perovskite oxides $La_{0.67}Ca_{0.33}MnO_3$ and $La_{0.5}Sr_{0.5}CoO_3$ at low temperatures (5 K >T > 0.3 K) and high magnetic field". New J. of Physics **14** 033026

(2013) Inverse Magnetocaloric and Exchange Bias Effects in Single Crystalline $La_{0.5}Sr_{0.5}MnO_3$ Nanowires Nanotechnology **24**, 505712

(2014) "Effect of size reduction on the structural and magnetic order in $LaMnO_{3+\delta}$ (δ≈ 0.03) nanocrystals: a neutron diffraction study" J. Phys.: Condens. Matter **26,** 025603

<u>Area: Instability in nanowires</u>

(2005) "Low frequency conductance fluctuations (1/f_ noise) in 15nm Ag nanowires- Implication on its stability" Physical Review B **72**, 113415

(2012) "**Liquid like instabilities in Gold Nanowires Fabricated by Focused Ion Beam Lithography"** Appl. Phys. Letts **101**, 163108

(2014) In-silico investigation of Rayleigh instability in ultra-thin copper nanowire in premelting regime J. Appl. Phys. **115**, 244303

Single nanowires devices as ultra-sensitive detector of charge and radiation:

Very recent work by the group has shown that certain types of nanowires when configured as a single nanowires device can act as ultra-sensitive detectors of photons which may open the path for single photon detection. The group is now trying to develop this type and reach sensitivity of single photon detector. A related , although not the same problem, is development of ultra-sensitive charge detectors. The group would like to embark on this challenging problem.

Some of the representative publications in this area

Rabaya Basori, K. Das, Prashant Kumar, K.S.narayan, A. K. Raychaudhuri
(2013) "**large photoresponse of cu:tcnq nanowire arrays formed as aligned nanobridges".** Appl. Phys. Lett. **102**, 061111 ;

Rabaya Basori, K. Das, Prashant Kumar, K.S.Narayan and A. K. Raychaudhuri
(2014) **Single CuTCNQ charge transfer complex nanowire as ultra high responsivity photodetector**.Optics express **22** , 4944

K. Das, S. Mukherjee, S. Manna, S. K. Ray*, A .K Rraychaudhuri
(2014) "single si nanowire (diameter ≤ 100nm) based polarization sensitive near-infrared photodetector with ultra-high responsivity." Rsc- Nanoscale **6** , 1123

Noise and fluctuations as a probe of materials science:

The group of Prof AKR have used and are using 1/f noise spectroscopy to investigate a number of phenomena in condensed matter physics. This involves metal insulator transition in doped Si, charge order transition in manganites , ferromagnetic insulating state of manganites, noise during electromigration, noise during oxygen migration , noise in single nanowires of Si and colossal magnetorsistive oxides and similar such systems. These measurements give information. That are often not available through measurements of resistivity which is an average property.

Some of the representative publications in this area

(2002) "**Measurement of 1/f noise and its application in materials science"**
Current Opinion in Solid State & Materials Science **60,** 67-85

(2000) "Universal conductance fluctuations in heavily doped single crystals of Si"
Phys. Rev Letts. **84**, 4681

(2001) :"Electric field induced migration of oxygen ions in epitaxial metallic oxide films : non-Debye relaxation and 1/f noise." Phys. Rev **B 64**, 104304

(2002)"Onset of long range diffusion and exponent of $1/f^{\alpha}$ noise in metal films with electromigration damage" Appl. Physics Letters **81**, 5165

(2003) " Low frequency random telegraphic noise (RTN) and 1/f noise in rare-earth manganite $Pr_{0.63}Ca_{0.37}MnO_3$ near the charge ordering transition",
Phys Rev**. B 67** , 174415

(2003)"Observation of non-Gaussian conductance fluctuations at low temperatures in P doped Silicon at the metal-insulator transition " .
Phys.Rev.Letts.**91,** 216603
(2006) " 1/f noise in nanowires- " Nanotechnology- **17,** 152
(2006) "Direct observation of large temperature fluctuations during DNA thermal denaturation" Physical Review Letts. **96,** 038102
(2006) " **Evolution of $1/f^{\alpha}$ noise during electromigration stressing of metal film: spectral signature of electromigration process**". J. Applied Physics **99,** 113701
(2012) "Non-Gaussian resistance noise in the ferromagnetic insulating state of a hole doped manganite." Phys. Rev. **85**, 045127
(2014) "Low-Frequency Resistance Fluctuations in a single nanowire (diameter _ 45nm) of a complex oxide and its relation to magnetic transitions and phase separation"
Applied Physics Letters **105**, 073117;

Physics of correlated oxides:

AKR group has been working on correlated oxides like transition metal oxides for some time. In recent years it has investigated current driven resistance state transition in such oxides. In such materials , when the doping level is low it shows an insulating state that is ferromagnetic in character. The recent work in the group has investigated the onset of metallic state in such ferromagnetic insulators on application of hydrostatic pressure. The AKR group is also investigating the "glassy electronic" state in such materials that freeze out the charge relaxation kinetically using measurement of charge and polarization fluctuation. A future endeavor .will be to tune the glassy electronic state by pressure/strain and investigate whether it gives rise to a quantum phase transition.

Some of the representative publications in this area

(2008) "Hot electron effects and non--linear transport in hole doped manganites"
Appl. Phys. Letters **93**, 182110
(2007) "Localized reversible nanoscale phase separation in $Pr_{0:63}C_{0:3}MnO_3$ single crystal induced by Scanning Tunneling Microscope Tip " Applied Phys. Letts. **91,** 143124
(2009) "Pressure (P > 8*GPa*) induced metallization of ferromagnetic insulating $La_{0:79}Ca_{0:21}MnO_3$" ,J. Appl. Phys. **106**, 023905
(2011) " Voltage bias induced modification of all oxide $Pr_{0.5}Ca_{0.5}MnO_3$ /$SrTi_{0.95}Nb_{05}O_3$ junctions",J. Appl. Phys. **109**, 083934
(2013) "Electric field driven destabilization of the insulating state in nominally pure $LaMnO_3$.,J.Phys.: Condensed Matter **25** 155605
(2014) " Electric Double Layer (EDL) gate controlled non-linear transport in nanostructured functional perovskite film" Applied Phys. Letts **104**, 083515

Physics and application of wide band gap semiconductor ZnO:

The AKR group has been active in this area since 2005. The early work focused on ZnO doped ZnO nanoparticles and nanowires and control of optical properties like band gap by Mg and Cd subtitution. Interesting results were obtained in visible emission from defects by environmental control using polar medium or electric double layer (EDL) or control of surface depletion layer by size control.

Currently the group is working on Thin Film Transistor (TFT) made from ZnO and is investigating new effects that can enhance their response and hence the applicability as detectors . These TFT's are made either from solution based deposition or as multilayered structure made by pulsed laser deposition (PLD). The group is investigating effect of polymer electrolyte gate on such ZnO- TFT. This type of gate creates an Electric-Double layer gate that can introduce large charge to the material that makes the channel in the TFT. Recently it has been discovered by the group that illumination of UV light on such EDL-FET ZnO-TFT leads to new effects that include gate controllable persistent photo conductivity and a synergetic response of the TFT with both gate and illumination.

Some of the representative publications in this area

(2006) "Structural and Optical properties of nanoparticles of $Zn_{1-x}Mg_xO$ grown by low temperature chemical route. J. Applied Physics **100**, 034315

(2007)" Structure and optical properties of Cd substituted ZnO ($Zn_{1-x}Cd_xO$) nanostructures synthesized by high pressure solution route". Nanotechnology **18** 115618

(2007) " Band gap variation in Mg and Cd doped Zinc Oxide nanostructres and molecular clusters."Phy. Rev B . **76**, 195450

(2008) "**Shape transition in ZnO nanostructures and its effect on blue-green photo luminescence",**Nanotechnology **19,** 445704

(2009) "**Photoreactivity of ZnO nanoparticles in visible light: Effect of surface states on electron transfer reaction".** Journal of Applied Physics **105**, 074308.

(2010) "Dynamics of light harvesting in ZnO nanoparticles". Nanotechnology **21** 265703

(2011) "Observation of a large gate- controlled persistent photoconduction in single crystal ZnO at room temperatures". Appl Phys.Letts **98**, 023501

(2011) "Field induced reversible control of visible luminescence from ZnO nanostructures",Appl.Phys. Letts **98,** 153109

(2013) "Enhancing photoresponse by synergy of gate and illumination in electric double layer field effect transistors fabricated on n-ZnO",Appl Phys.Letts **103**, 231105

(2015) "Mobility enhancement in Electric Double Layer gated n-ZnO UV photodetector by synergy of gate and illumination: A photo Hall study" Appl. Phys.Letts **106**, 041102

(2015) "Synergistic ultraviolet photoresponse of a nanostructured ZnO film with gate bias and ultraviolet illumination". Journal of Applied Physics **117**, 105705 (2015)

Scanning Probe Microscopy

The AKR group has been actively using different form of scanning probe microscopy to study physics of materials. They have also worked on fundamental aspects of micro-cantilever used in AFM that modifies the Force Spectroscopy. It has used extensively STM based Scanning Tunneling spectroscopy (STS) and Scanning Tunneling Potentiometry (STP) using a temperature variable high vaccum STM to carried out extensive studies on Charge Ordred and Colossal Magneto Resistive manganites . One of the important early result was to establish how a gap opens up at the Fermi level in the density of states (DOS) when the Charge ordered insulating state sets in and how it collapses under a magnetic field. Extensive STS study on manganites also showed how a gap in DOS builds up near T_C and the closing of the gap below T_C leads to release of carriers at the insulator-metal transition point at T_C. Using local tunneling conductance map a close relation of grain boundary contribution to MR and the DOS was established.

Some of the representative publications in this area

(1997)" Direct measurement of charge ordering gap in $Nd_{0.5}Sr_{0.5}MnO_3$ using vaccum tunneling" J. Phys : Condensed Matter (letters) **9,** L 355

(2000) "Collapse of charge ordering gap of $Nd_{0.5}Sr_{0.5}MnO_3$ in an applied magnetic field" J.Phys. Condens. Matter (letters) **12**, L 101

(1999) " The density of states of hole-doped manganites : A scanning tunneling microscopy/spectroscopy study" , Phys. Rev. **B 59** , 5368

(2003) "Non-linear electrical transport through artificial grain boundary junctions in epitaxial thin film of $La_{0.7}Ca_{0.3}MnO_3$" . Phys. Rev **B 68,**144409

(2003)" Depletion of density of states at the Fermi level in metallic colossal magnetoresistive Manganites" Phys Rev **B 68,** 134428

(2006) "Spatially resolved study of electronic transport through grain boundaries in nanostructered films of colossal magnetoresistive (CMR) manganites." Physical . Review B **74**, 085412

(2007)" A method to quantitatively evaluate Hamaker constant using the jump-into-contact effect in Atomic Force microscopy" Nanotechnology **18,** 035501

(2009) "Scanning Thermal Microscope Study of a Metal Film Under Current Stressing: Role of Temperature Inhomogeneity in Damage Process". J.Phys D: Applied Physics **42** , 035503

(2010) "**The effect of intrinsic instability of cantilever on static mode atomic force spectroscopy "** Nanotechnology **21** 045706

(2012) "Tuning the instability in Static Mode Atomic Force Spectroscopy as obtained in an AFM by applying an electric field between the tip and the substrate." Ultramicroscopy **122** 19