FY2013 Annual Report
Femtosecond Spectroscopy Unit

Assistant Professor Keshav Dani

Abstract

In recent years, the ability to synthesize, engineer & observe materials on the nanometer length scale has led to novel phenomena and applications. On the other hand, modern lasers deliver powerful, ultrashort pulses of light allowing us to observe the interaction of electrons and atoms on the femtosecond timescale. Together, these technologies allow us to study new paradigms in light-matter interaction – with femtosecond temporal resolution and nanometer spatial resolution. In the Femtosecond Spectroscopy Unit, we direct these abilities towards different areas of study:

(a) *Novel 2D Materials & Heterostructures*, where we search for new functionality in materials with applications in optics, electronics and energy;

(b) *Techniques for Neuroscience & Drug Delivery*, where femtosecond pulses and nanoscale, biocompatible devices offer new possibilities in imaging and interacting with the brain.

(c) THz devices and applications, investigating the generation of broadband THz radiation and applying this to a variety of materials and devices.

Furthermore, the Femtosecond Unit Spectroscopy has continued the development of experimental capabilities in pursuit of the study of the above mentioned phenomena.

1. Staff

- Dr. Keshav M. Dani, Professor
- Dr. Eleftheria Kavousanaki, Researcher
- Dr. Peter Hale, Researcher
- Dr. Michael Man, Researcher
- Dr. Bala Murali Krishna, Researcher
- Catherine Chin, Graduate Student
- Athanasios Margiolakis, Graduate Student
- Elaine Wong, Graduate Student
- Taka Harada, Graduate Student
- Andrew Winchester, Graduate Student
- Dr. Saikat Talapatra, Visiting Professor
- Ms. Yoko Fujitomi, Research Administrator

2. Collaborations

- **Theme: Transient Photoconductivity Dynamics in two-dimensional materials and heterostructures**
  - Type of collaboration: Joint research
  - Researchers:
    - Professor Ajayan Pulickel, Rice University, Houston, TX, USA
    - Soumya Vinod, Rice University, Houston, TX, USA
    - Dr. N. T. Narayanan, RCSI-Central Electrochemical Research Institute, Karaikudi, India
- **Theme: Low Energy Electron Spectroscopy of Transition Metal Dichalcogenides**
  - Type of collaboration: Joint research
  - Researchers:
    - Professor Saikat Talapatra, Southern Illinois University, Carbondale, IL, USA
    - Professor P.M. Ajayan, Rice University, Houston, TX, USA
    - Dr. A.D. Mohite, Los Alamos National Lab, Los Alamos, NM, USA
    - Dr. G. Gupta, Los Alamos National Lab, Los Alamos, NM, USA
    - Dr. H. Yamaguchi, Los Alamos National Lab, Los Alamos, NM, USA
- **Theme: Drug Delivery using Femtosecond Pulses**
  - Type of collaboration: Joint research
  - Researchers:
    - Professor Jeff Wickens, OIST, Okinawa, Japan
    - Dr. Takashi Nakano, OIST, Okinawa, Japan
- **Theme: Optics of graphene from quantum dots to infinite sheet**
  - Type of collaboration: Joint research
  - Researchers:
    - Professor Nic Shannon, OIST, Okinawa, Japan
    - Rico Pohle, OIST, Okinawa, Japan

3. Activities and Findings

3.1 Novel 2D Materials and Heterostructures

Optically induced magnetic moments in symmetric graphene quantum dots [E. G. Kavousanaki, K. M. Dani]

In the past few years there has been a lot of interest in the properties of graphene nanostructures, as they can be tuned depending on their size, shape and edge geometry [1,2]. In FY2012 we started working on the electronic and optical properties of graphene quantum dots. In particular, using the tight binding model for graphene [3], we calculated the optical selection rules in triangular zigzag quantum dots and showed that due to the triangular symmetry allow only transitions between states of specific rotational symmetry are allowed.

In FY2013, we extended our work by studying differently shaped structures. We showed that the above optical selection rules are very similar in hexagonal quantum dots, where now the hexagonal symmetry determines the allowed transitions. Moreover we showed that this result is independent of edge type, as long as the triangular or hexagonal symmetry is retained.

Another direction of our work in FY2013 was to study how an external magnetic field would affect these results, especially since there has been a lot of researc in inducing and controlling magnetization in To this end, we introduced an external magnetic field by a Peirls substitution in the tight binding model [3]. Our results showed that while the optical selection rules do not change, states of different symmetry behave differently in a magnetic field. By calculating the average angular momentum for each eigenstates, we found that the quantum dot eigenstates exhibit a linear, Zeeman-like behavior for magnetic fields under 10T. This property in combination with the optical selection rules allowed us to propose a scheme in which we can optically excite a nonzero magnetic moment in these nanostructures.

References

[1] F. Molitor, J. Güttinger, C. Stampfer, S. Dröscher, A. Jacobsen, T. Ihn and K. Ensslin, J. Phys.: Condens. Matter 23, 243201 (2011).
[2] O. Yazyev, Rep. Prog. Phys. 73, 056501 (2010).
[3] A. Castro-Neto, F. Guinea, N. Peres, K. Novoselov, and A. Geim, Rev. Mod. Phys. 81, 109 (2009).

Photoconductivity measurements on artificially stacked two-dimensional heterostructures - Graphene, hexagonal Boron Nitride (hBN)/Graphene heterostructures and Molybdenum disulphide (MoS2) [B. M. Krishna, Michael Man, C. Chin, T. Harada, S. Talapatra, K. M. Dani]

Beyond the discovery of graphene, a number of other two-dimensional materials have been discovered in recent times with properties spanning the entire range of electronic structures, from insulator to metal, high specific surface areas and display interesting properties [1-5]. These 2D materials are important in various applications such as optoelectronics, spintronics, catalysts, chemical and biological sensors, super capacitors, solar cells, and lithium ion batteries. In this study, we measured the photoconductivie response of graphene, hBN and hBN/Graphene and MOS2 for our studies.

Our samples are prepared by first separating individual sheets from the bulk materials by breaking the weak van der Waals bonds between the layers in solution via sonication (Liquid Phase Exfoliation). This creates dispersions of single layer and few-layer sheets of the required materials in various solvents. Such dispersion can easily form films by vacuum filtration and drop casting methods with thicknesses that range from nanometers to tens of micrometers. Compared with mechanical exfoliation, solution-based exfoliation is an efficient method for producing large quantities of layered materials.

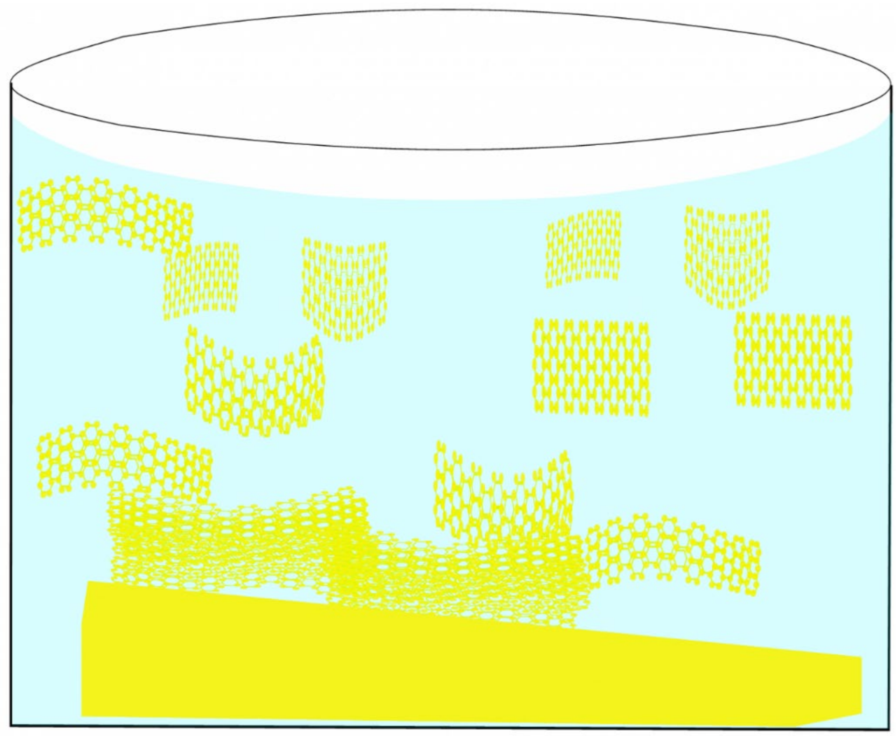

Figure 1: Liquid phase exfoliation of graphene.

To measure the photoconductivity response of the films prepared via liquid phase exfoliation, we use a technique called terahertz time-domain spectroscopy (THz TDS). In this technique, the material is photo-excited with UV/VIS or NIR pump pulses and probed with a time-delayed terahertz pulse. The terahertz pulses are modified due to the pump induced carriers and allow extracting the time dependent transient photoconductivity of the photocarriers. We used a ~70 fs, 800 nm, 1 kHz laser pulses to photoexcite electron and hole pairs in the sample. A sub-picosecond THz probe pulse, derived from the same laser system, was generated using optical rectification in a ZnTe nonlinear crystal. The instantaneous transient photoconductivity of carriers was measured as a function of pump probe delay.

Below we describe the results obtained for the different samples studied – Graphene, hBN/G Heterostructures and MoS_2.

Graphene:

Graphene monolayers were fabricated from bulk graphite by liquid phase exfoliation is represented in Fig.1. Here, we exfoliate graphite powder using common solvent DMF to isolate mono, bi- and few layer graphene nanosheets by simple sonication for 5 to 6 hours. The supernatant solution is collected in a beaker and sonicated for 1 to 2 hours to get dispersed mono layers. These monolayer graphene nanosheets are allowed to reassemble the stack by Van der Waals forces. The artificial stacked graphene solution was used to make thick film on quartz substrate by simple drop casting method. Relaxation dynamics of artificially stacked graphene nanosheets are studied by recording the differential pump-induced signal ΔT as a function of THz probe delay τ. Here we measured the change in the transmission of peak of the THZ probe field. For all the pump powers studied, the THz transmission decreases rapidly after photoexcitation and recovers on the time scale of few picoseconds. The THz transparency of graphene was decreased after photoexcitation corresponding to free carrier's generation and increases conductivity. We observed two relaxation time scales, first one around 1 ps is associated mainly with carrier trapping and a second one is ~10's of ps is related to recombination of carriers.

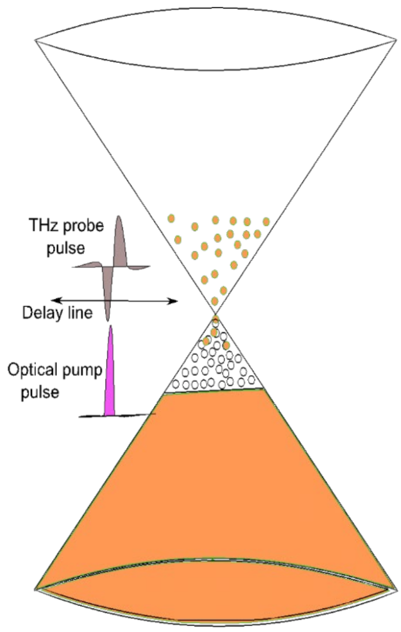

Figure 2: Non-equilibrium band structure of graphene induced by optical pump and probes with THz pulses

hBN/Graphene heterostructures:

hBN/G heterostructures were prepared by self-assembling liquid phase exfoliated hBN and graphene layers. We measured a change in transmission (ΔT/T) of the peak THz probe pulse on photoexcitation versus pump-probe delay for the different heterostructures. The semi-metallic graphene phase of the sample shows a strong negative ΔT/T associated with a decrease in the transmitted THz probe, due to screening of the THz electric field by the mobile photoexcited carriers. For the insulating h-BN phase of the samples, there is no change in the THz peak transmission on photoexcitation, since the 800 nm pump pulse is well below the bandgap of h-BN and hence results in no photoexcited carriers. For the intermediate h-BN:G 1:1 and 1:3 samples, we observe a fast negative ΔT/T signal, indicative of mobile photocarriers shortly after photoexcitation. The negative peak, indicating higher transient photoconductivity, grows with increasing ratio of graphene in the hBN/G heterostructure. Thus, we note the ability to tune the photoconductivity of the heterostructure from the insulating phase to the semi-metallic phase simply by tuning the ratio of hBN to G in the heterostructure. Further, for the hBN:G 1:3 heterostructure, one clearly sees the development of a ΔT/T positive signal shortly after photoexcitation. This signal, not seen in the parent insulating and semi-metallic hBN and G phases respectively, is indicative of different opto-electronic behavior in the heterostructures.

MOS_2:

In order to understand the recombination and trap state dynamics of the photocarriers in exfoliated MoS_2 nanosheets, thin films of these materials were deposited on quartz and were studied using optical pump and THz probe measurement. Here, we use 400 nm pump pulse to photo-excite the carriers. The decay in conductivity of the photocarriers closely follows a bi-exponential time dependence with a very fast decay component τ_1 ~ 9 ps and a slower decay component τ_2 ~ 90 ps, indicating the presence of multiple relaxation processes. The fast initial decay time τ ~ few ps is a signature of photocarriers being trapped by surface trap states. The longer decay time τ ~ few hundreds of ps is manifestation of electron-hole recombination in the trap states present between the valence band and conduction band. The time scales observed in our measurements are similar to those found in the case of photo excited carrier relaxation times of mechanically cleaved few layers of MoS_2 crystals.

References

[1] Q. H. Wang. et al., Nature Nanotechnology, 2012, 7, 699.
[2] Ruben Mas-Balleste,Cristina Gomez-Navarro,Julio Gomez-Herrero and Felix Zamora, Nanoscale, 2011, 3, 20.
[3] L. Britnell, et al., Science, 2013, 340, 1311
[4] A. K. Geim & I. V. Grigorieva, Nature, 2013, 499, 419.

Low Energy Electron Microscopy studies of corrugation of MoS_2 on Si substrates. [M. Man, A. Winchester, S. Talapatra, K. M. Dani]

Low Energy Electron Microscopy (LEEM) is a powerful and versatile surface sensitive technique that utilizes a range of complementary analysis methods and it is particular suitable for the characterization of material surfaces, ultrathin films and 2D materials 1-3]. In FY2013, working with our collaborators at the Rice University and the Los Alamos National Laboratory, we concentrate our effort in the study of a recently discovered two-dimensional (2D) transition metal dichalcogenide, molybdenum disulphide (MoS_2), which has attracted substantial interest due to its semiconducting properties, and potential applications in electronics, optics and energy storage. However, electronic transport and optical properties of these 2D materials are affected by the presence of structural disorder such as formation of domain structures, corrugation and interaction with the substrate. We studied monolayer and multilayer/multidomain MoS_2 flakes synthesized by Chemical Vapor Deposition (CVD) [4-5], a promising technique and widely used method to produce large area MoS_2, for a variety of technological applications. We examined the lattice orientation and domain boundaries in these MoS_2 flakes in detail using low energy electron microscopy and diffraction (LEEM/LEED). These investigations show that as grown single layer MoS_2 samples as well as samples transferred onto various substrates exhibit substantial corrugation due to the presence of the underlying substrate. Furthermore, we found that the amount of corrugation decreases with increasing number of MoS_2 layers. These investigations throw significant light in the understanding of multi domain structural existence and substrate mediated structural changes in atomically thin layers of CVD grown MoS_2.

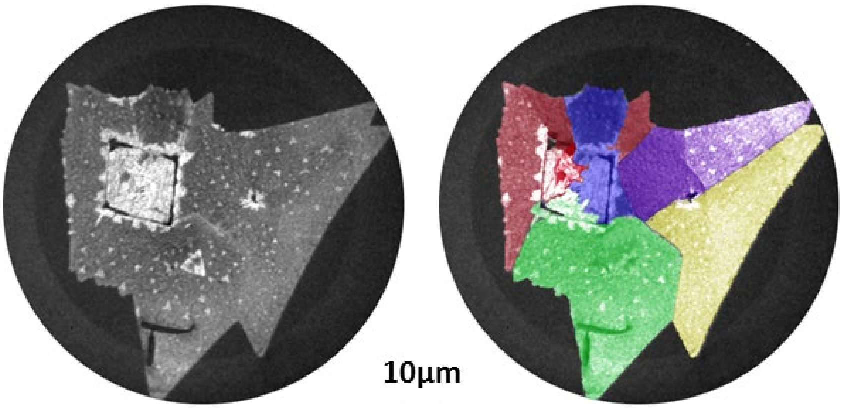

Figure 3: (left) Bright field image of a single layered MoS_2 flake with brighter region representing area of higher layer thickness. (right) Color-coded image of the same flake with different lattice orientation identified by dark field imaging technique. It shows the polycrystalline nature of the irregular flakes.

References

[1] E Bauer, Rep. Prog. Phys. 57, 895-938 (1994).
[2] M S Altman, J. Phys.: Condens. Matter 22, 084017 (2010).
[3] K L Man and M S Altman, J. Phys.: Condens. Matter 24, 314209 (2012).
[4] Sina Najmaei, et al., Nature Materials 12, 754–759 (2013).
[5] Arend M. van der Zande, et al., Nature Materials 12, 554–561 (2013).

3.2 Femtosecond Spectroscopy Techniques for Neuroscience and Drug Delivery [C. Chin, P. Hale, B. M. Krishna, K. M. Dani]

In continuation of a project initiated in FY2012, the Femtosecond Spectroscopy Unit, in collaboration with the Wickens Unit at OIST, has been investigating the application of Femtosecond Pulses of light in Neurosceince for imaging and interacting with neural functions through controlled chemical release.

In FY2013, we have demonstrated an on-demand, subsecond, pulsatile, dopamine delivery system using femtosecond lasers as a non-destructive external stimulus. By varying the laser intensity and exposure time, we can arbitrarily and precisely control the concentration and temporal profile of the dopamine delivery. Given the fast timescales on which neural signaling operates, this rapid temporal control provides the ability to mimic the temporal profile of chemicals released during important neurochemical processes. Future directions lie in investigating the applicability of this fast delivery system to a wide range of neurochemicals that can be encapsulated in liposomes. The technique promises future potential for the delivery of natural and synthetic therapeutic compounds involved in rapid biological signaling; stimulating multiple brain locations simultaneously by combining with recently developed femtosecond techniques to control the size and shape of the stimulated volume engineering the response of the delivery system to different laser wavelengths to allow for multi-channel operation; and potentially replacing lost functionality due to neural degeneration via ‘neurochemical prosthesis’.

References

[1] Takashi Nakano *et. al.*, Scientific Reports 4, 5398 (2014).

3.3 THz Devices and Applications

In FY2012 we were able to demonstrate high electric field (beyond 1 kV/cm) THz radiation produced from a photoconductive interdigitated antenna. Using a thin (20 um) ZnTe crystal for detection we observed a detectable bandwidth approaching 25 THz. The spectroscopic capabilities were demonstrated with a PTFE tape. Previous studies [1,2] have demonstrated several resonances from 6 - 19 THz, in good agreement with our results . This large bandwidth was associated with the high power, short pulses generated from our oscillator and compression module.

In FY2013 we have verified that the bandwidth observed is a consequence of the ultrafast pulses, even when the antenna substrate has a long carrier lifetime (SI-GaAs). By varying the pulse width or pulse power onto the antenna we have revealed the available bandwidth in the range 15 – 35 fs and 2 – 30 nJ respectively. Modelling the idealized output from an interdigitated antenna [3] we have confirmed the broad bandwidth obtained in our measurements, and for comparison shown how these compare to a substrate with a faster recombination time (LT-GaAs).

Using the common facilities available in OIST we have designed and fabricated our own bespoke THz antenna structures. With a mask-less alignment we can generate a variety of interdigitated antenna devices for use in THz generation and detection. High field, broadband emission is observed with device yields of over 80%.

In collaboration with Ecole Normale Superieure, Paris, we have started an investigation into the resonant properties of micro cavity arrays for THz emission. Using THz time domain spectroscopy, our initial results show a strong dependence of the resonance frequency on the micro cavity dimensions.

References

[1] Y. C. Shen, P. C. Upadhya, E. H. Linfield, H. E. Beere and A. G. Davies, Ultrabroadband terahertz radiation from low-temperature-grown GaAs photoconductive emitters, Appl. Phys. Lett. 83, No. 15, 13 (2003).
[2] F. D’Angelo, Z. Mics, M. Bonn and D. Turchinovich, Ultra-broadband THz time-domain spectroscopy of common polymers using THz air photonics, Optics Express 22 10 (2014).
[3] J. Madeo, N. Jukam, D. Oustinov, M. Rosticher, R. Rungsawang, J. Tignon and S.S. Dhillon, Frequency tunable terahertz interdigitated photoconductive antennas, Electronics Letters 46 No. 9 (2010).

3.4. Further Development of Experimental Capabilities

Angle Resolved Photoemission Spectroscopy (ARPES) & In-Situ Sample Preparation with Low Energy Electron Microscope [M. Man, K. M. Dani]

As an ongoing effort to extend the capability of the Low Energy Electron Microscope, which was installed in Q4 FY2012, several upgrades have been installed in FY2013. First of all, we installed an UV light source, which enable us to perform angle-resolved photoemission spectroscopy measurement and investigate the valance band electronic structure of materials. Furthermore, to facilitate in situ preparation of samples in a well-controlled ultrahigh high vacuum environment, we installed two compact molecular beam epitaxy sources, an alkaline metal dispenser and a gas dispenser. These additional components enable us to synthesis thin film or complex composites through mixing of various elements. In particular, we aim to fabricate complex 2D materials in the LEEM/PEEM. Structural, chemical and electronics properties of these materials can all be comprehensively characterized by the microscope. Following that, the opto-electronics properties and other properties of these materials can then be further investigated by other ultrafast optical techniques in the unit and by the rest of the extensive facilities on campus.

Magneto-Optical Spectroscopy [E. Wong, M. Man, K. M. Dani]

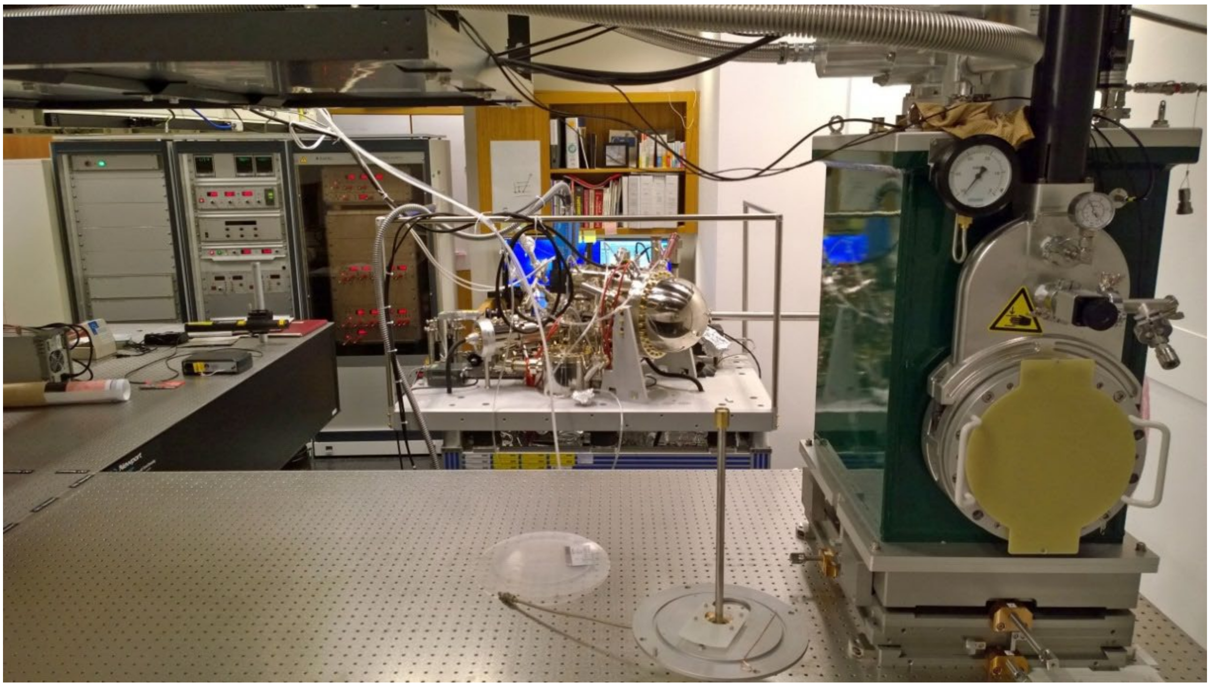

Figure 4: View of new 17 T magnet installation.

In FY2013, the Femtosecond Spectroscopy Unit installed a 17 Tesla Cryogen Free Superconducting Magnet & Variable Temperature Insert (VTI) System in order to extend their experimental capabilities towards high-field magneto-optical spectroscopy.

The magnet is made up of a single horizontal-field solenoid and the sample is mounted inside the bore of the magnet from the front face of the solenoid. The system utilizes two-stage pulse tube cryocoolers that allows the bore to be cooled down to 2.6 K. Two optical windows at the front and back face of the system allow access to incoming and transmitted laser beams.

Radiation heat transfer from the external environment is minimized via high-purity aluminium radiation shield coupled with multilayer superinsulation between the shield and the outer wall. The radiation shield is attached to the first stage of the cryocoolers and cools to approximately 35 K. The second stage of the cryocoolers are linked to the magnet and has a base temperature of < 4.2 K. High temperature superconductor current leads link the 1st and 2nd stages of the cryocoolers.

These capabilities will shortly be used to study the magnetic properties of two-dimensional magnetic semi-conductors and their heterostructures.

UV Generation [P. Hale, A. Margiolakis, K. M. Dani]

UV (UV) generation has been achieved to give the unit access to high energy photons, stretching to 6 eV. By mixing the fundamental 800 nm beam and focusing into different cuts of BBO crystals we have extended the wavelength range down to 266 nm. With these high energy photons we are now able to access new physics and investigate new systems with high repetition rate, ultrafast pulses. Graphene is a prime example of this due to the saddle point observed at the M-point of the Brillouin zone. Here, the band gap is 4.5 eV and can be probed with a single 266 nm photon to reveal the carrier dynamics of this relatively unexplored part of the dispersion curve.

4. Publications

4.1 Journals

1. Bauer, E., Man, K. L. M., Pavlovska, A., Locatelli, A., Menteş, T. O., Niño, M. A. & Altman, M. S., Fe3S4 (greigite) formation by vapor–solid reaction. *Journal of Materials Chemistry A* 2, 1903-1913, doi:DOI 10.1039/C3TA13909C (2013).
2. Mariserla, B. M. K. & Narayana Rao, D., Influence of solvent contribution on nonlinearities of near infra-red absorbing croconate and squaraine dyes with ultrafast laser excitation. *Journal of Applied Physics* 114, 1-8, doi:DOI 10.1063/1.4823817 (2013).
3. Mariserla, B. M. K., Venktramaiah, N. & Narayana Rao, D. Optical transmission control in graphene oxide and its organic composites with ultrashort laser pulses. *Journal of Optics* 16, 1-6, doi: DOI 10.1088/2040-8978/16/1/015205 (2014).

4.2 Books and Other One-Time Publications

Nothing to report.

4.3 Oral and Poster Presentations

1. Dani, K. M., *Applications in Femtosecond Spectroscopy*, Invited Seminar, Los Alamos National Lab, Los Alamos, NM, USA (June 3, 2013).
2. Hale, P., Madeo, J., Chin, C., Dhillon, S., Mangeney, J., Tignon, J. & Dani, K. M., *Broadband THz generation using Interdigitated Photoconductive antennas with a 15 fs, high power,* CLEO: Science and Innovations June 9-14, 2013, San Jose Convention Center, San Jose, CA, USA (June 12, 2013).
3. Cross, A., Chin, C., Harada, T., Mariserla, B. M. K., Wong, E. L., Parkin, I. & Dani, K. M., *Terahertz Spectroscopy of Photocatalytic Titanium Dioxide Films*, Invited Talk, Microwave/Terahertz Science and Applications 2013, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai, CHINA (July 22, 2013).
4. Connolly, M., Hale, P. & Dani, K. M., *Interdigitated Antennas for Broadband Terahertz Generation*, Poster Presentation, Colloquium XXVII, Rice Quantum Institute, Rice University, Houston, Texas, US (August 2, 2013).
5. Dani, K. M., *Applications of Femtosecond Spectroscopy: From Broadband Thz generation to Drug Delivery*, Invited Seminar, Lund University, Lund, SWEDEN (August 5, 2013).

6. Dani, K. M., *Application of Ultrafast & Nonlinear Spectroscopy: From 2D materials to mimicking neurofunctioning*, Invited Seminar, Institute of Solid State Physics, University of Tokyo, Kashiwa Campus, Tokyo, JAPAN (November 20, 2013)
7. Dani, K. M., *Introduction to 4D Electron Microscopy*, Invited Talk, Beam Physics Workshop 2013, Okinawa Inst. of Science and Technology, Graduate Unversity, Okinawa, JAPAN (November 28, 2013).
8. Dani, K. M., *Ultrafast Spectroscopy of Novel Materials*, Invited Seminar, Tata Inst. of Fundamental Research, Mumbai, India (December 23, 2013).
9. Dani, K. M., *Applications of Femtosecond Spectroscopy: From 2D Materials to Mimicking Neuro-Functioning*, Invited Seminar, University of Hyderabad, Hyderabad, INDIA (January 6, 2014).
10. Dani, K. M., *Application of Ultrafast & Nonlinear Spectroscopy: From 2D materials to mimicking neurofunctioning*, Invited Seminar, Indian Institute of Sciences (IISc), Bangalore, INDIA (January 8, 2014).
11. Mariserla, B. M. K., *Electronic properties of self-assembled hBN/G heterostructures studied by optical pump terahertz probe technique*, Invited Seminar, Indian Institute of Technology, Indore, INDIA (January 10, 2014).
12. Man, M. K. L., *Ultrafast Imaging of Electron Dynamics in Nano-Engineered Materials, Invited Seminar, National Center for Electron Microscopy*, Lawrence Berkeley National Laboratory, USA (February 25, 2014).
13. Pohle , R., Kavousanaki, E., Dani, K. M. & Shannon, N., *Growing up in the Spot Light: Optics of Graphene from Dot to Sheet*, American Physical Society (APS) March Meeting 2014, Denver, Colorado, US (March 3, 2014).
14. Man, M. K. L., Yamaguchi, H., Najmaei, S., Lei, S., Ajayan, P. M., Lou, J., Gupta, G., Mohite, A. D. & Dani, K. M. *Characterization of Large Area Molybdenum Disulphide by Low Energy Electron Microscopy*, American Physical Society (APS) March Meeting 2014, Denver, Colorado, US (March 4, 2014).
15. Mariserla, B. M. K., Chin, C., Harada, T., Soumya, V., Taha-Tijerrina, J., Nguyen, P., Chang, P., Ajayan, P. M., Narayanan, N. T. & Dani, K. M., *Optical pump-THz probe measurements of self-assembled h-BN/G heterostructures*, American Physical Society (APS) March Meeting 2014, Denver, Colorado, US (March 5, 2014).
16. Connolly, M., Winchester, A., Hale, P., Dani, K. M. & Talapatra, S., *Temperature Dependent Raman Studies of Liquid Phase Exfoliated* MoS_2, American Physical Society (APS) March Meeting 2014, Denver, Colorado, US (March 6, 2014).

17. Kavousanaki, E. & Dani, K. M., *Manipulation of electronic states in triangular graphene quantum dots using optical selection rules*, American Physical Society (APS) March Meeting 2014, Denver, Colorado, USA (March 7, 2014).

18. Kavousanaki, E., Pohle, R. & Dani, K. M., *Manipulation of magnetization in symmetric graphene quantum dots using optical selection rules*, Poster Presentation, Joint ISSP-OIST symposium: Lighting up new frontiers - from Tokyo to Okinawa, from materials to neurons, Okinawa Institute of Science and Technology Graduate University Okinawa, Japan (March 11, 2014)

19. Mariserla, B. M. K., Chin, C., Harada, T., Soumya, V., Taha-Tijerrina, J., Nguyen, P., Chang, P., Ajayan, P. M., Narayanan, T.N., Dani, K. M., *Novel opto-electronic behavior of hBN/G van der waals hetrostructures*, Poster Presentation, Joint ISSP-OIST symposium: Lighting up new frontiers - from Tokyo to Okinawa, from materials to neurons. Okinawa Institute of Science and Technology Graduate University Okinawa, Japan (March 11, 2014)

20. Winchester, A., Ghosh, S., Feng, S., Elias, A. L., Mallouk, T., Terrones, M. & Talapatra, S., *Electrochemical Characterization of Liquid Phase Exfoliated 2D Layers of Molybdenum Disulfide*, Poster Presentation, Joint ISSP-OIST symposium: Lighting up new frontiers - from Tokyo to Okinawa, from materials to neurons, Okinawa Institute of Science and Technology Graduate University Okinawa, Japan (March 11, 2014)

21. Winchester, A., Connolly, M., Hale, P., Dani, K. M. & Talapatra, S., *Low Temperature Phonon Shifts in Liquid Phase Exfoliated MoS2*, Poster Presentation, Joint ISSP-OIST symposium: Lighting up new frontiers - from Tokyo to Okinawa, from materials to neurons, Okinawa Institute of Science and Technology Graduate University Okinawa, Japan (March 11, 2014)

22. Mariserla, B. M. K., Chin, C., Harada, T., Vinod, S., Taha-Tijerina, J., Nguyen, P., Chan, P., Narayanan, N. T., Ajayan, P. M. & Dani, K. M., *Optical pump terahertz probe of two-dimensional heterostructures*, Invited Talk, TeraNano4 2014, Institute of Laser Engineering, Osaka University at Suita Campus, Osaka, JAPAN (March 14, 2014).

23. Dani, K. M., *Femtosecond Light in Future Technologies*, Invited Talk, Nature Café 2014, Grand Front Osaka, Osaka, JAPAN (March 14, 2014).

5. Intellectual Property Rights and Other Specific Achievements

Nothing to report.

6. Meetings and Events

6.1 Seminar

- Title: Terahertz time-domain polarimetry: how and why?
- Speaker: Professor Diyar Talbayev, Department of Physics and Engineering Physics, Tulane University, USA.
- Date: April 8, 2013
- Venue: OIST Campus, Lab 1

6.2 Seminar

- Title: Quantum Cascade Laser field control in the Terahertz domain
- Speaker: Jean Maysonnave, PhD student, Laboratoire Pierre Aigrain, Ecole Normale Supérieure, France.
- Date: April 12, 2013
- Venue: OIST Campus, Lab 1

6.3 Research Visit

- Visitor: Prof. Ivan Parkin, Department of Chemistry, University College London, UK.
- Visitor: Davinder Bhachu, Department of Chemistry, University College London, UK.
- Date: May 11, 2013 - May 12, 2013

6.4 Research Visit

- Visitor: Prof. Junichiro Kono, Department of Electrical & Computer Engineering and Department of Physics & Astronomy,Rice University, USA
- Visitor: Prof. Masayoshi Tonouchi, University of Osaka Japan
- Date: May 19, 2013 - May 21, 2013

6.5 Seminar

- Title: Materials and Applications: Carbon Nanotubes, Graphene and Beyond Graphene
- Speaker: Prof. Saikat Talapatra, Associate Professor at the Department of Physics, Southern Illinois University, USA.
- Date: May 21, 2013
- Venue: OIST Campus, Lab 1

6.6. NanoJapan 2013 Mid Program Meeting

- Date: July 5, 2013 - July 8, 2013
- Venue: OIST Campus

6.7 Research Visit

- Visitor: Jerome Tignon, Laboratoire Pierre Aigrain, Ecole Normal Superieure, Paris, France.
- Date: July 9, 2013 - July 17, 2013

6.8 Research Visit

- Visitor: Yuecel Kaptan, PhD student, TU Berlin, Germany.
- Date: July 9, 2013 - August 23, 2013

6.9 Seminar

- Title: A brief overview of machine vision and assessment of at stereo vision algorithm performance
- Speaker: Oliver Hamilton, PhD student, Cranfield University, UK.
- Date: October 25, 2013
- Venue: OIST, Lab 1

6.10 Seminar

- Title: Transient excitons at metal surfaces
- Speaker: Professor Hrvoje Petek, Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, USA.
- Date: February 14, 2014
- Venue: OIST Campus, Lab 1

6.11 Joint ISSP-OIST Symposium: "Lighting up new frontiers - from Tokyo to Okinawa, from Materials to Neurons"

- Date: March 10-11, 2013
- Venue: OIST Campus
- Co-organizers:
  - Institute for Solid State Physics (ISSP), University of Tokyo, Japan
  - Femtosecond Spectroscopy Unit, OIST, Japan
- Speakers:
  - Hidefumi Akiyama, ISSP
  - Sile Nic Chormaic, OIST
  - Yoshihisa Harada, ISSP
  - Jiro Itatani, ISSP
  - Yohei Kobayashi, ISSP
  - Yabing Qi, OIST
  - Nic Shannon, OIST
  - Shik Shin, ISSP
  - Mukhles Sowwan, OIST
  - Tohru Suemoto, ISSP
  - Jeff Wickens, OIST
  - Yoko Yazaki-Sugiyama, OIST

7. Others

Nothing to report.