Photonic Nano-Metamaterials: Science Meets Magic

Ekmel Ozbay

Nanotechnology Research Center, Bilkent University
Bilkent, Ankara 06800 TURKEY

Abstract: The word “magic” is usually associated with movies, fiction, children stories, etc. but seldom with the natural sciences. Recent advances in metamaterials have changed this notion, in which we can now speak of “almost magical” properties that scientists could only dream about only a decade ago. In this article, we review some of the recent “almost magical” progress in the field of photonic nanometamaterials.

Keywords: Metamaterials, Photonics, Nanolithography

Starting in high school physics, we learn that light is made of a combination of electric and magnetic fields. As light propagates through matter, conventional materials only react to the electric field, in which this interaction results in most of the optical effects that we know of, such as refraction, diffraction, lensing, imaging, etc. 40 years ago, Prof. Veselago asked the question “what if matter also interacts with the magnetic field of light?” [1]. He showed that when both electric and magnetic properties were negative ($\varepsilon<0$ and $\mu<0$), the solution of the Maxwell equations resulted in an index of refraction with a negative sign.

The theoretical predictions of Prof. Veselago had to wait ~30 years for the first experimental realization of these engineered materials that are also called metamaterials. The seminal work of Sir John Pendry [2] provided the blueprints for the experimental realization of metallic based resonant structures that are called split ring resonators (SRRs), which exhibit $\mu<0$ at the resonance frequencies. Smith et al. [3] combined an array of SRRs ($\mu<0$) and an array of metallic wires ($\varepsilon<0$) in order to create double negative composite metamaterials. In such a case, the famous “right handed rule” between the electric and magnetic fields becomes left-handed, in which these materials are known as left-handed materials (LHMs) or negative index materials (NIMs).

Besides negative refraction, scientists have shown that metamaterials can also be used to achieve “almost magical” applications such as subwavelength imaging, super lenses, perfect lenses, cloaking, chirality etc. Although the early experiments were performed at microwave frequencies, it took only a few years for the scientists to downscale these structures to optical frequencies [4]. These nano-scale metamaterials are now called as photonic metamaterials.

As shown in Figure 1, SRRs can be fabricated with dimensions reaching nanometer scales. The nano-scale SRR acts as an LC resonator with a resonance frequency [5]. More importantly, the typical size of these resonant inclusions is approx. 10 times smaller than the vacuum wavelength of the light at the resonance frequency. Although a single-layer SRR structure can easily be fabricated on a dielectric surface, it is relatively difficult to stack these structures due to the tight alignment tolerance requirements. Prof. Harald Giessen and his group members have reported a new method where metamaterials in the near-infrared spectral region can be fabricated using a layer-by-layer technique [6].

Conventional SRRs provide a neat way to achieve magnetism at optical frequencies. In order to excite the magnetic resonance of the SRR, the incoming light should propagate in a direction that is parallel to the SRR.
Terahertz Wave Emission from Intrinsic Josephson Junctions of High-Tc Superconducting Mesas

Lütfi Özyüzer1*, H. Köseoğlu1, F. Türkoğlu1, Y. Demirhan1, Y. Şimşek2, T. Yamamoto3, K. Kadowaki1, H. B. Wang2, P. Müller2

1Department of Physics, Izmir Institute of Technology, Izmir, Turkey
2Department of Physics, University of Erlangen, Erlangen, Germany
3University of Tsukuba, Tsukuba, Japan
4National Institute of Materials Science, Tsukuba, Japan

Abstract—The natural structure of single crystal Bi2Sr2CaCu2O8+d (Bi2212) is considered as c-axis tunnel junctions between sets of superconducting CuO2 planes, which are called intrinsic Josephson junctions (IJJs). Recently, we experimentally demonstrated that rectangular IJJ mesa structures of Bi2212 can be used as a compact solid state generator of continuous, coherent and polarize terahertz (THz) radiation source, which a reliable source does not exist around this frequency range. The simple voltage-frequency relation in AC Josephson effect is valid and higher frequencies require higher bias for over 600 junctions in series. The mesa structures were fabricated on various Bi2212 single crystals, and current-voltage and THz emission characteristics were investigated. We will discuss recent experimental results of THz wave generation from Bi2212 crystals.

Terahertz sensing and imaging is a rapidly developing technology with applications including security, medicine, quality control etc [1]. There is a need for compact continuous wave (CW) solid-state terahertz source with practical power. There are some available CW sources such as quantum cascade lasers that only work above 1.2 THz. Multiplication of Gunn diodes produces low output powers. Backward wave oscillators are bulky and have low output power at higher frequencies. Optically pumped THz gas lasers are also bulky and not tunable.

Single crystal of high temperature superconductors (HTSs) e.g. Bi2Sr2CaCu2O8+d (Bi2212), forms perfect layered structure as a superlattice and these natural stacks of SIS multi-junctions are called intrinsic Josephson Junctions (IJJs). Each junction is 1.5 μm thick and separated by Bi-O and Sr-O layers. The experimental observation of IJJ in Bi2212 single crystals was an important achievement because close proximity of tunnel junction couples Josephson junctions [2]. Since the IJJs are naturally stacked along the c-axis of Bi2212 single crystals, they exhibit anisotropic electrical behaviors. The tunneling current-voltage (I-V) characteristics of IJJs along the c-axis of Bi2212 exhibit large hysteresis and multiple branches.

The successful observation of THz emission by our group stimulated studies on THz generation from intrinsic Josephson junctions of Bi2212 mesas [3]. The fundamental frequencies of observed emission were as high as 0.85 THz and radiation power was up to 0.5 μW which are not achieved before. It is shown that the emission frequency is proportional to the 1/w, where w is with of mesa and indicating that Josephson plasma frequency has to match the cavity resonance of mesa for successful emission. Recently, one order larger radiation power (~ 5 μW) and higher harmonics (up to 4th corresponds to 2.5 THZ) of resonance have been obtained [4].

Many theoretical studies accomplished to explain mechanism of THz generation from Bi2212 mesas. There is no consensus right now and need more experimental input for complete proof of a theory. In this study, we will present generic properties of THz radiating mesas, such as resistivity versus temperature (R-T) and I-V [5]. Figure 1 shows an example of bolometer response during I-V measurement. The frequency of the emission is around 0.35 THz for this mesa. Furthermore, one of the radiating mesas will be shown that Josephson voltage frequency relation has to be satisfied for the THz emission.

Figure 1: (a) Current-voltage characteristics of 100x300 μm2 mesa at 20 K (b) Bolometer response during I-V measurements. The arrows show THz emission voltages.

* ozyuzer@iyte.edu.tr

REFERENCES

Investigation of High Frequency Performance of Graphene Field Effect Transistor Using a Self Consistent Transport Model

Ercag Pince\textsuperscript{1}, Coskun Kocabas\textsuperscript{1}\textsuperscript{*}

\textsuperscript{1}Department of Physics, Bilkent University, Ankara 06800, Turkey

Abstract—Extremely high field effect mobility together with the high surface coverage makes graphene a promising material for high frequency electronics application. We investigate the intrinsic high frequency performance of graphene field effect transistors using a self-consistent transport model. The self-consistent transport model is based on a nonuniversal diffusive transport that is governed by the charged impurity scattering owing to the presence of the charged impurities on the substrate. Experimentally feasible top gated transistor geometry is used for the calculations. The output and transfer characteristics of graphene field effect transistors are characterized as function of impurity concentration and dielectric constant of the gate insulator. Important high frequency device parameters such as transconductance, output resistance and power gain have been investigated. These results reveal the essential design considerations of the graphene transistors for radio frequency operations.

Recent advances of chemical vapor deposition of graphene on large area substrates stimulate a significant research effort searching for new applications of graphene in the field of unusual electronics such as macroelectronics. Graphene can function as an effective semiconductor or a transparent conducting coating for large area displays and photovoltaic devices. Recent developments in scaling graphene films opens up new opportunities for flexible electronics without losing any electronic performance\textsuperscript{1}. Extremely high field effect mobility of graphene together with the large area deposition process\textsuperscript{2}, could provide alternative solutions for the challenges of traditional organic materials. Operation at radio frequencies is one of the main challenges of the organic based field effect transistor owing to the poor field effect mobility. Therefore radio frequency analog electronics could be an immediate high-end application of graphene.

In this Letter we provide a framework based on an analytical model for understanding the design considerations of the graphene based transistors operating at radio frequency band. Although high frequency analog electronics is a well established field for inorganic semiconducting materials, the effects of unusual transport properties of mono-atomic graphene sheets at high frequencies are widely unknown.

The unique band structure makes graphene unlike the other 2D confined electronic systems. In the present analysis of the radio frequency devices we consider a self-consistent transport model developed by S. Adam et al.\textsuperscript{3} based on a charged impurity scattering reaction. This model explains the most of the observed electrical behavior of graphene sheets, e.g. nonuniversal minimum conductivity and ultrahigh mobility of suspended graphene layers. The beauty of the model is that it requires only two parameters, density of charged impurities and the distance between the impurity and graphene layer.

For a bias point, the carrier density is a function of position along the graphene layer. Knowing the gate voltage dependence of the conductivity, we can calculate the carrier density as a function of position by exploiting the self-consistent transport model. We have considered the constant contact resistance $R_c$ of 1.2 kΩ between the source/drain electrodes and the graphene layer. Figure 1a shows transfer and output curves for a device with a channel length of 1 μm and channel width of 1 μm. In this calculation we have used a 50 nm HfO2 as a gate dielectric. For these calculation, the only empirical parameter that we used is impurity concentration of the dielectric and contact resistance between the electrodes and the graphene.

In summary, we deducted the graphene based RF device performance by using the self-consistent model. Device parameters critical to evaluate the RF device applications such as transconductance, power gain and cutoff frequency are examined to a later extent. Therefore, we also observed a high frequency dependence on charged impurity scattering. Cleanest samples with charged impurity levels of $2 \times 10^{11}$ have $f_c$ around 25 GHz for 1 μm channel length. Most importantly, we showed that even devices with a very poor on/off ratio can provide power gain at suitable biasing conditions.

*Corresponding author: cckocabas@fen.bilkent.edu.tr

\begin{thebibliography}{9}
\bibitem{2} X. S. Li, et al. Science 324 (5932), 1312 (2009).
\bibitem{3} S. Adam, E. H. Hwang et al. Proceedings of the National Academy of Sciences of the United States of America 104 (47), 18392 (2007)
\end{thebibliography}
Embedded Subwavelength-Scale Discretized Displacement Sensing in Silicon Integrated Photonic Circuits

E. Bulgan

1School of Engineering, Ozyegin University, Istanbul 34662, Turkey

Abstract- Silicon photonic devices with embedded MEMS have recently seen significant interest. Precise characterization and operation of such devices in the nano/micro-system level is critical. Hereby, a novel embedded optical sensing technique for subwavelength-scale displacement measurements with discretized characteristics by dynamic control is introduced.

Because of its transparency and high confinement feature, silicon is an attractive platform for integration of microelectronics and photonics, called as “Silicon Photonics” [1], in order to bring compact device sizes and volume economics. Thus, research efforts towards silicon photonics have recently seen significant interest from the telecommunications and future all-optical computing areas. Owing to the low cost and high extinction ratios achievable by nano/micro-electromechanical system (NEMS/MEMS) driven optical devices, such silicon photonic devices with embedded NEMS/MEMS as optical add-drop multiplexer (OADM) [2], ring and microdisk resonators as narrow-band filters [3,4], photonic crystal (PC) line-defect waveguide optical switches [5,6], optical modulator [7], and most recently optical switches using physical contact of silicon waveguides [8,9] have already been studied.

Silicon photonic devices with embedded NEMS/MEMS technology utilize either in-plane or out-of-plane motion to accomplish their task. Characterization of such devices is realized either by actuation under optical microscope for post-micron-level motion ranges, or actuation under scanning electron microscope (SEM) for submicron-level motion ranges. Ultimate device characterization, therefore, depends on the quality and evaluation accuracy of the series of images taken consecutively under the corresponding microscope at various actuation levels. Hence, employment of images for device motion characterization causes measurement errors from several tens to hundreds of nanometers during evaluation stage for SEM and optical microscope uses, respectively. Some scientists, on the other hand, even prefer to characterize the optical performance as a function of the actuation voltage or energy applied to the system alone, because of the difficult and tedious work required, and high levels of uncertainty involved. Without proper characterization of devices where precise motion or distance in the nano/micro-system level is critical, full understanding of the discussed concept, or proper operation or control of the system becomes impossible. Currently, such levels of distances/displacements are barely measurable with external means of such techniques as atomic force microscopy (AFM), several other approaches [10-13], which are effort-intensive. In addition, they are usually only for testing purposes and cannot be integrated into the device level.

An approach using physical contact of silicon nanowire waveguides as optical connections has recently been reported [9]. The technique utilized change of optical transmittance in the Evanescent Wave Region (EWR) and coupling in the near-field between silicon nanowire waveguides as a function of the distance they are apart. Physical-contact provides sensitivity even to subwavelength displacement levels as a function of waveguide tip geometry and relative positioning of the adjacent waveguide pairs and is applicable to various wavelengths.

In this paper, we introduce a novel embedded optical sensing technique for subwavelength-scale displacement measurements with discretized characteristics by dynamic control using the aforementioned physical contact displacement sensing method. The technique is schematically illustrated in Fig. 1. The light coupled to the input waveguide is divided between the two output waveguides of the splitter. As depicted in Fig. 1, divided lightwaves propagate through Path 1 and Path 2 towards the two optical sensing connections. Displacement from the monitored MEMS motion source gets transferred through a rigid beam towards the sensing connections so that one or both of the connections placed in parallel allow or prevent transmission from the splitter towards the main output. By changing the ratios of the input light split to both waveguides in the splitter, it becomes possible to address the weight of the sensing characteristic curve of the two to be used in the measurement. Hence, the technique enables dynamic control of the optical displacement sensing character. As a result, one can easily define the combination of the desired sub-curve regions of various physical-contact-based displacement sensors to achieve the optimum performance needed. An example to such a configuration is illustrated in Figs. 2(a) and (b). While Fig. 2(a) depicts characteristics of two physical-contact-based displacement sensors without the introduced concept, Fig. 2(b) shows combined optical sensing characteristic realized by proper splitter control when both connection geometries are identical, and zero-hundred and hundred-zero percents for splitting ratios are used before and after 300 nm displacements, respectively.

In conclusion, a novel optical sensing technique is designed to equip researchers and engineers with guidelines for reliable and customizable subwavelength-scale displacement measurements with dynamically controllable discrete characteristics. The technique enables compact, high-sensitivity, embedded in-plane subwavelength-scale distance/displacement sensors. The approach can be employed as an optical distance/displacement sensor in demanding silicon photonics devices as an embedded tool, and in acoustical, flow, mechanical displacement sensing.

*Corresponding author: erdal.bulgan@ozyegin.edu.tr
MEMS and Microsystem Technologies for Microsensors and Biological Microdevices

Haluk Külah

1 METU MEMS Center, Ankara, Turkey
2 METU, Electrical and Electronics Engineering Department, Ankara, Turkey

Abstract-
This presentation introduces MEMS in general and microsensors and biological microdevices in more specific, including their applications with examples from the literature. In the second part of the talk, related projects at METU-MEMS Center will be presented.

Since the first introduction in 1970’s, MEMS technology is becoming popular in many different application areas, including military, automotive, and consumer electronics, as it provides cheap, small, and smart sensors and actuators. This technology is especially critical for biomedical applications, resulting in a new research area shortly called BioMEMS. BioMEMS can be defined in general as “devices or systems constructed using techniques inspired from micro-fabrication that are used for processing, delivery, manipulation, analysis, or construction of biological and chemical entities [1].” Application areas of BioMEMS range from diagnostics to micro-fluidics, systems for drug delivery, tissue engineering, and implantable biomedical systems.

Figure 1. DNA electrophoresis system developed at METU-MEMS [3]

One of the most interesting application areas for this technology is the micro total analysis systems (Micro-TAS). Biological samples can be analyzed in a very small area with considerably reduced cost and time, by forming micro-fluidic channels on silicon substrate and combining them with on-chip electronics. Some examples for such applications include on-chip electrophoresis systems, polymerized-chain-reaction (PCR) units, DNA sequencing chips, and complex lab-on-a-chip devices [2-6]. These kinds of systems can be incorporated with wireless electronics technology and can be implanted inside the body for real time measurement of blood chemical values. Even further, it is possible to form small reservoirs on the same chip for storing drugs and releasing them to the body according to the analysis results. Similar systems can be used for diagnosis purpose. In this case, the technology is used to detect predefined sort of cells, viruses, bacteria, proteins, or enzymes in blood or in another liquid environment. This application is very critical for prevention of diseases as well as early detection of them. Another interesting application for BioMEMS is smart bio-implants. Combining this technology with complex CMOS circuitry, it is possible to produce biocompatible, small, smart and esthetic implants.

There are currently various BioMEMS related projects going on at METU-MEMS, including DNA electrophoresis systems [3], dielectrophoresis chips for cell separation [4], gravimetric sensors for cancer cell detection, microvalves and pumps for lab-on-a-chip systems [5], and electrochemical sensors for bacteria and toxin detection. Figure 1-3 show pictures of some prototypes developed in our group.

Figure 2. Dielectrophoresis chips developed at METU-MEMS [4]

REFERENCES
Thermal Conductivity of Magnetic Nanofluids in External Magnetic Field

Alper Elkatmis¹*, Merve Yüksel², Seyda Bucak², Necdet Aslan³
¹TÜBİTAK UME-National Metrology Institute, Kocaeli 41470, Turkey
²Department of Chemical Engineering, Yeditepe University, Istanbul 34755, Turkey
³Department of Physics, Yeditepe University, Istanbul 34755, Turkey

Abstract- It is expected that the thermal conductivity of fluids upon addition of nanoparticles enhances with increasing volume fraction or by applying an external magnetic field. In this study, Fe₃O₄ magnetic nanoparticles were used and enhancements in thermal conductivity both in water and in heptane were observed with increasing volume fraction and by applying an external magnetic field. The M-H curves of the same sample with different concentrations were also observed.

A magnetic fluid (or ferrofluid) is a stable colloidal suspension of magnetic nanoparticles with a mean diameter of about 10 nm suspended in a carrier liquid [1]. Nanoparticles contain only a single magnetic domain and can thus be thought as permanent magnets in a carrier liquid and can be oriented by an external magnetic field gradient. Some properties like viscosity, thermal conductivity or density can be changed by applying an external magnetic field. Thus, magnetic fluids have a wide range of potential technical and biomedical applications [2]. Enhancement of thermal conductivity upon addition of nanoparticles is very important since ferrofluid is heavily used in heat transfer and bearing systems.

In this study, the ferrofluid was synthesized based on the procedure reported by Wooding et al. [3], in which co-precipitation of Fe(II) and Fe(III) salts by NH₄OH at 60 °C was carried out in the presence of a fatty acid surfactant. Magnetic particles were dispersed in water and heptane and thermal conductivities were measured in the presence of magnetic field. Figure 1 shows the change of thermal conductivity in heptane as a function of temperature and volume fraction.

Figure 1. Thermal conductivity curves for the magnetite heptane at different concentrations.

The external magnetic field enhances the thermal conductivity due to the magnetic forces on ferrofluid particles. Magnetic field was created by keeping a DC magnet at a fixed distance from the container including nanoparticle. Applied magnetic field was perpendicular to the hot wire equipment utilized in measuring the thermal conductivity. The increase of thermal conductivity as a function of magnetic field for heptane is presented in Figure 2. As seen, nearly 30 seconds after the magnetic field is increased from 0 to 20G and from 20 to 40 G the thermal conductivity increases 0.1 percent and 0.25 percent, respectively. The magnetic fluids carrying superparamagnetism feature give zero coercivity and remanence on a hysteresis loop [4]. Figure 3 displays the magnetization curves that were obtained by Vibrating Sample Magnetometer (VSM) for heptane at different concentrations.

Figure 2. Enhancement of Thermal Conductivity in Heptane on Application of Magnetic Field.

Figure 3. Magnetization curves of magnetite heptane at different concentrations as determined by VSM device.

In summary, the thermal conductivities of magnetic particles dispersed in water and in heptane were measured in the presence of a magnetic field. The results showed that thermal conductivity in both water and heptane enhanced with external magnetic field.

We thank Dr. Uğur Topal from TÜBİTAK UME for helping to carry out VSM equipment for this research.

*alper.elkatmis@umes.tubitak.gov.tr

Humidity Sensing Properties of an Isopropanol-induced and Alkaline pH-triggered Bovine Pancreatic Trypsin Film

Cagatay Ceylan1*, Salih Okur2, Evren Culcular2
1Department of Food Engineering, Izmir Institute of Technology, Izmir, Turkey
2Department of Physics, Izmir Institute of Technology, Izmir, Turkey

Abstract—The possibility of an alcohol-induced and alkaline pH-triggered bovine pancreatic trypsin gel film as a humidity sensor was analyzed using quartz crystal microbalance (QCM). The morphology of the film was characterized using Atomic Force Microscopy (AFM). The protein gel film was found to be sensitive to humidity changes. The response of the humidity sensor was explained using dynamic Langmuir model. The average values of adsorption and desorption rates between 11% RH and 84% RH were calculated as $1533 \text{ M}^{-1}\text{s}^{-1}$ and $2.83E-3 \text{ s}^{-1}$ respectively. The equilibrium constant and average Gibbs free energy of three humidity adsorption and desorption cycles were obtained as 5.420E+05 and -13.203 kJ/mol, respectively.

Water adsorption and desorption property of protein molecules determine their structure and function. Similarly, gels and thin films formed from proteins are also strongly influenced by the interaction between protein, water and other co-solvent molecules [1].

In this study we analyzed the film produced after the gelation of bovine pancreatic trypsin on the gold QCM plate. Gelation takes place after the dissolved protein in 1 mM Tris-HCl buffer and isopropanol mixture in equal volumes was further mixed with 20% 10 mM NaOH. The protein film remains on the surface after the gel is removed with subsequent washes with pure ethanol and water from the gold QCM plate.

![Figure 1. a) 2D, b) 3D AFM view of bovine pancreatic trypsin gel film.](image)

The overall morphology of the film formed of the QCM electrode was visualized using AFM as shown in Figure 1. The film is observed to contain nanostructures on the surface. QCM technique was employed for the characterization of the adsorption/desorption kinetics of the film for increasing and decreasing humidity values between 11 and 97 % RH for equal time intervals to investigate the rate of adsorption and desorption rate of any residual adsorbed mass on the film due to change in the moist concentration as a result of humidity change and its fit to the dynamic Langmuir model as shown in Figure 2. The relationship between the surface adsorption kinetics and frequency shift ($\Delta f$) of QCM can be expressed as following:

$$\frac{d\Delta f}{dt} = (\Delta f_{\text{max}} - \Delta f) k_s C - k_d \Delta f$$

where $\Delta f$ and $\Delta f_{\text{max}}$ are the QCM resonance frequency shifts, $k_s$ and $k_d$ are the adsorption and desorption rate constants, $C$ is the concentration of water molecules in air, $t$ is the time. The standard steam tables were used to determine the partial pressure of water vapor at related temperature [2].

![Figure 2. QCM frequency shifts for adsorption and desorption cycles between 11% and 97% RH (a) and various RH values as a function of time (b), RH dependence of the frequency shifts (c) and the fit to the dynamic Langmuir model (d).](image)

The adsorption and desorption processes were observed to be reversible with the relaxation time 0.718546 s. The response of the humidity sensor was explained using dynamic Langmuir model. The average values of adsorption and desorption rates between 11% RH (concentration of 1.060E-04 M) and 84% RH (concentration of 9.060E-04 M) were calculated as 1533 M$^{-1}$s$^{-1}$ and 2.83E-3 s$^{-1}$ respectively. The equilibrium constant and average Gibbs free energy of three humidity adsorption and desorption cycles were obtained as 5.420E+05 and -13.203 kJ/mol, respectively.

In summary, we analyzed the film produced after the gelation of bovine pancreatic trypsin on the gold QCM plate using QCM technique and AFM. The protein film is shown to be sensitive to humidity changes and to have a reversible adsorption/desorption behavior like a sensitive humidity sensor.

* cagatayceylan@iyte.edu.tr

Thin film sensor microsystem for accurate and real-time measurement of humidity levels

Omer Mermer1,2, Salih Okur2, Mahmut Kus3, Şeref Ertul4, Mevlüt Bayrakçı5, Mustafa Yılmaz4
1 Ege University, Department of Electrical and Electronics Engineering Bornova/Izmir/TURKEY
2 Izmir Institute of Technology, Department of Physics Urla/Izmir/TURKEY
3 Selçuk University, Department of Chemical Engineering, Selçuklu/Konya/TURKEY
4 Selçuk University, Department of Chemistry, Selçuklu/Konya/TURKEY

Abstract— This study focuses on the optimization and characterization of calix[4]arene derivative based humidity sensor film fabricated using drop-casting method between thermally evaporated gold electrodes with 15 um separation and 300um channel width on a glass substrate. The change of resistance was monitored with increasing and decreasing relative humidity (RH) up to 94%. The resistance, capacitance, and AFM techniques were used for the characterization. This value promises great potential for humidity sensor at room temperature operations.

Monitoring and control of humidity is essential for industrial progress of the world such as petroleum industry, medical equipments, food industry and the manufacturer of moisture sensitive products. Furthermore clean rooms, greenhouses, research and developments labs are all environments that are highly effected by moisture levels and require constant monitoring [1–2]. Thin films of calix[4]arene derivatives have been widely used in chemical sensors. Due to their zeolite-like capacity and selectivity, Calix[4]arenes became promising materials for sensor applications. The functional groups at the upper and lower rims determine their selectivity in host-guest interactions and physical properties [3]. Calix[4]arene derivatives have been used in recent times as gas sensors applications [4-6].

Figure 1 Chemical formula and full name of special design Calix[4]arene

In this work, special design calix[4]arene molecules were designed for humidity sensor application. Chemical structure and full name of this molecule is given in Figure 1. Calix[4]arene based sensors were fabricated drop-casting method between thermally evaporated gold electrodes with 15 um separation and 300um channel width on a glass substrate. The change of resistance was monitored with increasing and decreasing relative humidity (RH) up to 84%. The resistance, capacitance, and AFM techniques were used for the characterization. The humidity response is depending on molecular structure of Calix[4]arene derivatives.

The DC resistance response curve Calix[4]arene thin film based sensor to cyclic humidity change is depicted in Figure 2(a) for different RH levels. The resistance decreases sharply with increasing humidity concentrations (adsorption process). On the other hand, during the desorption process, the humidity level is turned back to the initial value, as a result, resistance recovers back to its initial value.

The resistance of Calix[4]arene based humidity sensor shows an exponential dependence on relative humidity RH as shown in Fig 2 (b). In order to determine time response of Calix[4]arene thin film humidity sensor, adsorption part of resistance change was fitted and was found response. The output voltage signal depicts the drop from the background voltage $V_{air}$ to the equilibrium value $V_{CO}$ that occurs when the CO gas enters the test chamber and its return to the background value when pure air enters the chamber. Response time $t_{90}$ (the time needed to obtain a result equal to 90% of the equilibrium signal) was 15 s and the recovery time $t_{r}$ (the time needed to bring the signal back to 90% of the background signal) was 70 s [7].

Figure 3 The dc resistance response for 84% RH

In summary, the electrical results show that Calix[4]arene thin films are very sensitive to humidity and give reproducible resistance kinetic behavior to humidity changes for short time periods. Our results open a new era to the high-sensitivity and high-selectivity gas sensor applications. This work was supported by TUBITAK under Grant No. TBAG-109T240.

*Corresponding author: omermermer@gmail.com

## CS Laboratories

- **Acton**
- **Hamamatsu**
- **Janis**
- **Raith**
- **Stanford**
- **M-Squared**
- **Toptica Photonics**
- **Litron Lasers**
- **Piezosystem Jena**
- **Axic**
- **CVI Melles Griot**
- **Laser Quantum**
- **Femtolasers**
- **Fabreek**
- **Frontier Semiconductor**

**Photon is our business**