Chapter 7

7.1 Conclusions

In conclusion, the aim of the current thesis is to develop a low-voltage thin film transistor by using a cost-effective, low band gap ion-conducting gate dielectric. Accordingly, I have synthesized a number of ion-conducting gate dielectric that has been used as a gate dielectric for the fabrication of high mobility n-channel and ambipolar TFT that required < 2V operating voltage. Also, I have used these ionic dielectrics to fabricate GFETs and GFET based chemical gas sensors.

In this framework, I have synthesized Li_2ZnO_2, the new ion-conducting gate dielectric through a sol-gel method, and successfully used this dielectric, low operating voltage thin-film transistors. The crystal structure of Li_2ZnO_2 dielectric was identified by the X-ray measurements. The crystallization temperature of this dielectric is 500 ^oC, which is much lower than the conventional dielectric. The crystalline nature of this dielectric is preferable because of the higher dielectric constant that originated from the mobile Li-ion. The roughness of dielectric is measured from AFM, which represents the compatibility of dielectric with a semiconductor. To recognize the optical properties of this material, a thin film of Li_2ZnO_2 has been fabricated on quartz and p^+-Si substrate. Transparency data of this film indicates that it has very much transparency in the visible region, which may be due to less scattering at the interface. The electric conductivity data of Li_2ZnO_2 thin film with MIM device structure reveal a high insulating nature of Li_2ZnO_2 that gave us the confidence to utilize this material as a gate dielectric of a TFT. To accomplish the applicability of Li_2ZnO_2 dielectric thin film, solution-processed SnO_2 (Tin Oxide) TFT was fabricated that required only 2V to saturate the drain current and showed the carrier mobility ~23 $cm^2 V^{-1} s^{-1}$, signifying the preeminent candidate for low voltage TFT application. Moreover, this device also shows an on/off ratio of 7x 10^3 which is reasonably good as a solution-processed low voltage TFT. In addition, in comparison to sodium beta alumina (SBA) dielectric, the Li_2ZnO_2 film required 300 ^oC lower processing temperature (500 ^oC) to reach the crystalline phase of the dielectric, indicating the major improvement of ion-conducting dielectric film fabrication for TFT applications.

The second target of this thesis works to fabricate ambipolar TFT using a low band gap ion-conducting gate dielectric containing trivalent indium (In) and gallium (Ga) ion. Accordingly, I have developed a crystalline thin film of $LiInO_2$ and $LiGaO_2$ via the solution-processed method. The required annealing temperature these two dielectrics is 550 ^oC to achieve the crystalline phase. The optical study of these thin films indicates the optical band gap of $LiInO_2$ and $LiGaO_2$ are 3.6 eV and 5.4 eV, respectively. Moreover, both of these dielectrics have moderate leakage current due to the impurity-free film. To realize the applicability of these two different crystalline phases on TFT performance, two separate devices were fabricated with $LiInO_2$ and $LiGaO_2$ dielectrics, respectively. The SnO_2 was used as a channel layer for both dielectrics. It was observed that both devices work as an ambipolar TFT with an operating voltage ~ 1V. It is known that SnO_2 can show ambipolar nature, in case it is doped in a proper way. In this case, p-type doping has been introduced to the dielectric/semiconductor interface part of SnO_2 thin film due to the thermal diffusion of In or Ga ion during the annealing process of SnO_2. Most interestingly, it was observed that the device with $LilnO_2$ dielectric shows a balanced ambipolar charge transport with electron and hole mobility values of 7 $cm^2 V^{-1} s^{-1}$ and 8 $cm^2 V^{-1} s^{-1}$, respectively. The on/off ratio under both types of operation is >10^2. Particularly, this ambipolar TFT has been utilized for low-voltage CMOS inverter fabrication.

In my third goal, I have fabricated large channel length (up to 5.7 mm) graphene field-effect transistors (GFETs) through a simple, cost-effective method that required thermally evaporated source-drain electrode, which is less cumbersome from the conventional photolithography based electrode deposition. The semiconducting nature of graphene has been achieved by Li^+ ion doping from the Li_5AlO_4 gate dielectric, which shows current saturation at a low operating voltage (~2V). The length scaling of these GFETs has been studied with channel length variation within a range from 0.2 mm to 5.7 mm. It was observed that the GFET with1.65 mm channel length shows optimum device performance with good current saturation. This particular GFET shows the 'hole' mobility of 312 cm^2 V^{-1} s^{-1} with an on/off ratio of 3. For comparison, GFET has been fabricated in the same geometry by using conventional SiO_2 dielectric that doesn't show any gate-dependent transport property, which indicates the superior effect of Li^+ of the ionic gate dielectric on current saturation.

Finally, I have fabricated a GFET based NH_3 sensor with a large channel length of 450 µm. The device characteristics are shown excellent low operation behavior within 2V, which is paving the path for portable TFT based chemical gas sensors. The fabricated device has also been tested for very low concentration ammonia under ambient environment conditions at 25˚C temperature, which shows the enormous potential for ammonia sensing for real-life applications. The average response time and recovery time of this GFET based sensor is ~40 sec and ~120 sec, respectively. A large change in Dirac point variation from 1.4V to 0.7V indicates its high sensitivity in the ammonium atmosphere.

7.2 Scope for future work

For this thesis work, I have fabricated high performance, low operating voltage n-channel TFT, ambipolar TFT, large channel length GFETs, and GFET based NH_3 sensor using ion-conducting gate dielectric on a silicon substrate (p^+-Si). However, there is a significant scope to extend those work in the future for more extensive study and different applications of those devices. Some important expectation from them are given below:

Low voltage transparent transistor: In this work, I observed that these dielectric thin films are transparent in the visible region. Therefore, we can fabricate the fully transparent transistor using the transparent substrate and electrode.

Low voltage ferroelectric memory transistor: A memory element based on the ferroelectric thin film transistor (FeTFT) is one interesting device because of its non-volatile data retention. Therefore, by using Li-ion containing ferroelectric gate dielectric, it is possible to fabricate low-voltage operation and short programming time memory.

Low voltage phototransistor: We can develop the low voltage metal oxide phototransistor using this ion-conducting dielectric based TFT for the detection purpose.

Low voltage light-emitting transistor: This fabricated transistor can be explored for the development of the low voltage light-emitting transistor in the application of a flat panel display.

Low voltage sensors: Thin film transistors (TFTs) based sensors have attracted great interest due to the high selectivity, repeatable response, and low-cost production. However, we have fabricated only the NH_3 gas sensor, but we can extend different sensors like biosensors; pressure sensors use different sensing materials with this low voltage transistor.