Colloidal Quantum Dots Nanocomposites Based Resistive Switching for Low-Power Resistive Random Access Memory

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Summary and Conclusions

Conventional memory technologies such as HDD, USB Flash drive, SSD etc., which have been being used as data storage devices over the past few decades, are failed to store the huge amount of data generated by the explosion of digital information and internet of things(IoT). The silicon-based technologies are facing several theoretical and practical limitations upon downscaling. Also, the Von Neumann architecture used in the current computes has a separate processing unit and storage unit; therefore, the data transfer speed is limited and this architecture consumes a lot of power. Therefore, it is essentially needed to design universal memory with high-density data storage, fast operation speed, the capacity of in-memory computing and low power consumption. RRAM is one of the most promising candidates for universal memory owing to its simple device structure, high stacking density, fast operation speed, the capability of in-memory computing, long retention time, high endurance cycles and low power consumption. The main aim of carrying out this research is to fabricate high-performance resistive switching memory devices with low power consumption. The RS behaviors of CdSe QDs and MoS_2 QDs in corporations with PVP have been explored in this thesis. This research revealed that the synthesized CdSe QDs and MoS_2 QDs in corporation with organic polymers could be potential active materials for the fabrication of high-performance and low-powered resistive memory devices.

6.1 Summary

In this thesis, the first resistive switching behavior of a CdSe QDs-PVP nanocomposites-based device was studied, where the CdSe QDs-PVP nanocomposites were sandwiched between ITO and Al electrodes. The colloidal CdSe QDs were synthesized via the hot injection method. To prepare the CdSe QDs-PVP nanocomposite, PVP was blended with CdSe QDs in chloroform. The successful synthesis of CdSe QDs was confirmed by XRD, absorption spectroscopy, and TEM studies. The surface morphology was checked by AFM. The CdSe QDs-PVP nanocomposite was spin-coated on a cleaned ITO-coated glass substrate followed by top Al electrode deposition in a thermal evaporation system to fabricate a device with the structure of Al\CdSe QDs-PVP\ITO. The fabricated device exhibited bipolar nonvolatile RS behavior with a highest I_{ON}/I_{OFF} of 10^5, high endurance greater than 4000 switching cycles, fast response time and stable RAM characteristics. The switching voltage window was −2V to +2V in this device. Though the device showed high I_{ON}/I_{OFF} and high endurance, the retention time was low (only 3500 s) in this device. The switching mechanism was explained from the potential well-like energy band diagram because of the formation of a nanoscale heterostructure of CdSe-PVP.

Next, another CdSe QDs-PVP nanocomposites-based device was fabricated by sandwiching the CdSe QDs-PVP nanocomposite layer in between two Al electrodes and the RS behavior of the Al\CdSe QDs-PVP\Al device was investigated. The CdSe QDs were synthesized using a hot injection method with slight modification from the previous one. The colloidal monodisperse CdSe QDs were confirmed by XRD, XPS, absorption and emission spectra and TEM measurements. The HOMO-LUMO gap of the CdSe QDs was confirmed by the STS spectra in STM. The surface morphology was checked by AFM. The energy band positions of CdSe QDs and PVP were determined from UPS spectra. The Al\CdSe QDs-PVP\Al device also exhibited bipolar nonvolatile RS with a maximum I_{ON}/I_{OFF} of 6.1×10^4, high endurance, fast response time and good RAM behavior. This device exhibited resistive switching within a very small voltage

window of −0.8V to +0.8V, which is essential for a low-power memory device. The ultimate power consumption by the device is only 4.16 μW in the on state and 80 pW in the off state, which is sufficiently low to be considered a low-power memory device. Also, the retention time of this device was more than 35,000 s which is much longer than the previously studied Al\CdSe QDs-PVP\ITO device. The switching mechanism in this device was explained by charge trapping and de-trapping in the QDs, as the QDs act as charge trapping centers when they are embedded in the polymer matrix. This study reveals that the Al\CdSe QDs-PVP\Al device can be used as a high-performance RRAM with ultralow power consumption.

Though CdSe QDs-based devices exhibited excellent nonvolatile resistive switching with low power consumption, the CdSe is a toxic material and human carcinogen. It causes cancer in the human body; therefore very dangerous to deal with it. So, less toxic and non-carcinogen materials are always preferable in any electronic device. MoS_2 has been found to be less toxic and non-carcinogen. Next, the MoS_2 QDs were synthesized to replace the toxic CdSe in the resistive switching device. The RS properties of the MoS_2 QDs-PVP based device were then explored by sandwiching the MoS_2 QDs-PVP nanocomposite in between ITO and Al electrodes. The MoS_2 QDs were synthesized using the thermal reduction of ammonium tetrathiomolybdate ($(NH_4)_2MoS_4$) in a nitrogen atmosphere and were characterized by XRD, absorption spectroscopy, XPS and TEM measurements. The MoS_2 QDs-PVP nanocomposite was spin-coated on an ITO substrate followed by top Al electrode deposition in a thermal evaporation system to fabricate a device with a structure of Al\CdSe QDs-PVP\ITO. The fabricated device also exhibited nonvolatile resistive switching with high I_{ON}/I_{OFF}, long retention time, high endurance, fast response time and good RAM behavior. The operating voltage was less than ±1.5 V and the ultimate power consumption were19 μW in the on state and 63 nW in the off state, which indicates very low power consumption for energy saving. In addition, the thermal stability of the device was checked by temperature-dependent I-V measurements, which were performed by simultaneously heating the device at a particular temperature during measurements. The device exhibited resistive switching with sharp SET and RESET up to 130 °C, which suggests that this device will be fully operational at very high temperatures also.

6.2 Concluding Remarks

In conclusion, CdSe QDs-PVP nanocomposites sandwiched between ITO and Al electrode exhibited bipolar resistive switching with high $I_{ON}/I_{OFF,}$ but the retention time was low and the switching voltage was large. Another CdSe QDs-PVP nanocomposites-based device in which Al was used as both the top and bottom electrodes also exhibited bipolar RS with high I_{ON}/I_{OFF} and lower operating voltage, therefore, consumed ultralow-power. Also, the retention time was significantly longer in this Al\CdSe QDs-PVP\Al device. The height of the energy barrier in the Al-PVP junction is lower than that of the ITO-PVP junction and this may be the reason for getting the low value of SET and RESET voltage in this device compared to previously reported ITO\CdSe QDs-PVP\Al device. Though the CdSe QDs-based devices show excellent resistive switching with low power consumption, the CdSe is a toxic material and has been found to be a human carcinogen. In search of less toxic and non-carcinogen material, MoS_2 QDs-PVP nanocomposite-based device was fabricated for RRAM application. The ITO\MoS_2 QDs-PVP\Al device also exhibited excellent resistive switching behavior with low power consumption. In addition, the RS stability with the temperature in the less toxic and non-carcinogen MoS_2 QDs-based device has been explored. It has been found that the MoS_2 QDs-based device can be operated smoothly in a hot temperature environment also. It is concluded that the CdSe QDs and MoS_2 QDs in corporation with organic polymers can be potential active materials for the fabrication of high-performance and low-powered resistive memory devices.

6.3 Future Work and Scopes

The main aim of this research work is to fabricate high-performance resistive switching devices with low power consumption. In this thesis, CdSe QDs-PVP nanocomposite with two different device structures (Al\CdSe QDs-PVP\ITO) and (Al\CdSe QDs-PVP\Al) and MoS_2

QDs-PVP nanocomposite have been used as active material in resistive switching memory devices. More nontoxic and non-carcinogen materials QDs and nanoparticles can be used as active material in RRAM devices, which are yet to be explored. Apart from that, several future works can be done to improve the RS behavior, which is listed below:

I. The ratio of QDs and PVP can be varied to find the optimum ratio for the best device performance.
II. More polymers can be blended with QDs to choose which polymer is best for the device performance. The LUMO energy of the QD should be lower than the LUMO of the polymer.
III. MoS_2-like materials which are less toxic and non-carcinogen, such as WS_2 QDs and SnS_2 QDs, can also be used.
IV. The surface ligands in the QDs can be varied and the effect of ligands on resistive switching can be explored.
V. The ligand exchange with some inorganic capping agents in QDs surface can be performed and explore the effect of light on the RS behavior.
VI. Neuromorphic computing in QDs-based resistive memory devices can be explored.