Analog and Digital Memristive Devices Based on Hafnium Oxide for Neuromorphic Applications

Finn Zahari

Memristive devices are extensively investigated as non-volatile memory elements due to their variable resistance that is adjustable by electrical stimuli. They are promising devices, e.g., for in-memory computing concepts and to emulate biological synapses in neuromorphic circuits. In biology, the plastic synaptic efficacy adapts to the common activity of the connected neurons. This feature is one basic principle of learning in biological neural networks, which show an impressive performance in pattern recognition, processing of noisy and unstructured data, and precise control of the human body while consuming only a few ten watts. Neuromorphic engineering aims to replicate biological data processing to extend the computing capabilities of traditional Si complementary metal-oxide-semiconductor (CMOS)-based integrated circuits (ICs), which are the backbone of today's digital information technology (IT). Novel computing architectures and devices are required to overcome the scaling limitations of digital computing technology, especially for modern data-intensive tasks. Nevertheless, the integration of memristive devices into CMOS technology is of special relevance to combine both novel neuromorphic and in-memory computing concepts with mature and highly-scaled ICs.

The exploited materials and physical mechanisms leading to memristive switching are manifold. This dissertation focuses on devices based on binary metal oxides. Two types of devices are explored. The first type is composed of $Nb/NbO_z/Al_2O_3/Nb_xO_y/Au$, in which switching is based on a variable Schottky barrier, modulated by applying a bias voltage. These devices show promising features for neuromorphic circuits, such as analog switching, self-rectifying current-voltage (*I*-*V*) characteristics, an intrinsic current compliance (CC), and no need for an initial electro-forming step. The possibility of tailoring the device performance for specific applications is desirable. Hence, the plasma conditions of the sputter deposition process are recorded with plasma probes to correlate them with material properties and *I*-*V* characteristics across 100 mm wafers. Therefore, transmission electron microscopy (TEM) and electron energy loss spectroscopy (EELS) measurements are also utilized. The findings pave the way for plasma-engineered devices. In the next development step, HfO_2 is replacing the Nb_xO_y due to its CMOS-compatibility. The *I*-*V* characteristics are statistically evaluated on the wafer level, the device stability (with and without bias) is investigated, and tailoring of different read-out and switching parameters by up to several orders of magnitude by adjusting sputter deposition conditions and thin film sizes is shown. Moreover, the remaining challenges towards CMOS integration are discussed. A profound knowledge of the device physics is beneficial for transferring the functionality into a novel CMOS-compatible device. Thus, synchrotron-based X-ray photoelectron spectroscopy (XPS) and depth-dependent hard X-ray photoelectron spectroscopy (HAXPES) are exploited to determine electronic and chemical properties of the incorporated materials of functional devices switched between different states in-situ. TEM and EELS measurements are further providing structural and chemical information. A device model is deduced that considers thermionic emission as the dominant current transport mechanism in a two-terminal metal-insulator-semiconductor (MIS) structure. Here, electron trapping/de-trapping within HfO_2 is the switching mechanism that influences the band bending within the semiconducting NbO_x, and thus, the overall resistance. The spectroscopic evidence for the purely electronic switching mechanism in HfO_2, in particular, and in interface-type memristive devices, in general, should be emphasized as an original contribution to the research on memristive devices. A CMOS-compatible device structure that potentially offers qualitatively similar characteristics as the investigated devices is further proposed.

The second type of memristive devices employed in this dissertation is based on the formation and dissolution of conductive filaments within a HfO_2 layer. In particular, fully CMOS-integrated resistive random access memory (RRAM) devices, which can be switched between two resistive states and which were developed and produced at the IHP in Frankfurt/Oder (Germany), are utilized. The inherent randomness of the switching process is exploited to emulate synaptic plasticity in two-layer neuromorphic networks with stochastic updating rules to learn and classify static images. The stochastic artificial neural networks (StochANNs) are trained in a supervised manner in experiments and simulations and in an unsupervised way in simulations, both with novel algorithms. The proof-of-principle of emulating stochastic synapses with the RRAM devices is given experimentally and in simulations. The unsupervised algorithm has further the potential to be used in more sophisticated network architectures. The RRAM devices are further used to store weights of a three-layer ANN trained for disease detection. The mixed-signal implementation with hardware synapses and software perceptrons shows that the devices can potentially be used for computing matrix–vector-multiplications (MVMs) directly in-memory, helping in diagnosing diseases directly at the point of care (POC) with low-cost devices and no need for transmitting sensitive medical data to the cloud.