Environments Adaptability and Failure Analysis of Nanoscale Vacuum Channel Transistors

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Abstract: *Metal-emitter-based nanoscale vacuum channel transistors with vertical surround-gate configuration were fabricated by using thin-film deposition and focus ion beam etching. Adaptability testing in different vacuum environments and failure analysis of the transistors were carried out to make the basis for stability enhancement and component performance improvement.*

Keywords: environments adaptability, failure analysis, air channel, transistor, emission stability

Introduction

Nowadays vacuum channel transistors with nanoscale feature sizes can be fabricated by using state-of-the-art integrated circuit manufacturing technologies [1–4]. The nanoscale vacuum channel transistors usually use metal electrodes separated by air gap of several decades nanometers. The air gap is less than the mean-free path of electrons in air so that the electrons can transmit through low-vacuum or even air between electrodes at room temperature without any scattering.

Although the physics of electron transmission in air ensures the nanoscale vacuum channel transistors higher electron velocity and better immunity to radiation than traditional silicon devices, the vacuum devices can be totally achieved by standard silicon fabrication process, or even with fewer process steps. Because the vacuum devices eliminate the need for semiconductors, some specific processes for silicon devices such as doping, oxidation, thermal processing and silicide formation are not necessary any more. Consequently, the vacuum devices are expected lower production costs.

The silicon devices are facing the fact that the Moore's Law will come to an end because of its physical limits, while the nanoscale vacuum channel transistors are expected potential candidates to maintain the Law for another longer period. However, after the proof of concept, the device performance, the operational reliability and long-term emission stability of the new devices in different circumstances are imminently to be verified.

Design and Fabrication

Transistor Design: The device architecture and the air gap we design are similar to those of Ref.2, but the device has different material system. Unlike silicon devices, the vacuum channel transistors can be built on many dielectric substrates, and they have more tolerant material choices on source, insulator and drain configuration. In our research, refractory metal, diamond and carbon nanotube are all tested and evaluated as the source materials.

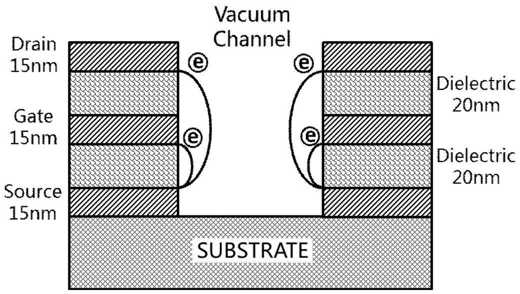

Fig. 1. Diagrammatic sketch of a vertical nanoscale vacuum channel transistor

Fabrication Process: The vacuum channel transistor is fabricated on a SiO_2/Si composite substrate, the electrode material is molybdenum (Mo) and the insulator is alumina (Al_2O_3) which are all formed by using electron beam evaporation.

First a 15nm Mo layer is deposited on the substrate and patterned as the source; then a 20nm Al_2O_3 layer and consequently another 15nm Mo layer are deposited and patterned as the gate; the second step is repeated to make the drain layer; and finally, a through hole from drain layer down to the substrate is etched by using focused ion beam (FIB) as the electron transmission channel.

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The scanning electron microscopy photo of the fabricated nanoscale vacuum channel transistor is seen in Fig.2.

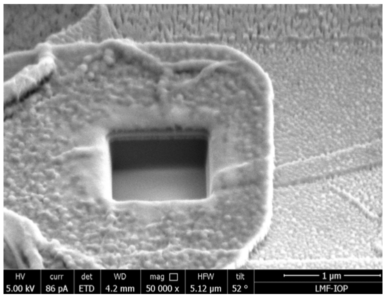

Fig. 2. SEM image of a square electron channel hole (1µm×1µm)

Test and Discussion

Environments Adaptability Test: The device is tested in a specific testing system. With adjustable pumping valve and nitrogen inlet, the system pressure can be easily ranged from high vacuum up to atmosphere. The power supplies provide stable voltage output with a resolution of 0.01V, and two Keithley 6485 picoammeters are used to monitor minor currents.

The source electron emission ability in different vacuum is first verified. The gate and the drain are connected to extract and collect electrons simultaneously in test. For each vacuum degree, the bias voltage on the gate and drain is slowly raised from zero to 20V, and the emission current for each voltage step is monitored. In a wide vacuum range from 10^{-7}Pa to 10^{4}Pa, it is found that the I-V performance for different vacuum degree doesn't change much, indicating the vacuum degree doesn't influence much on the electron emission of the device.

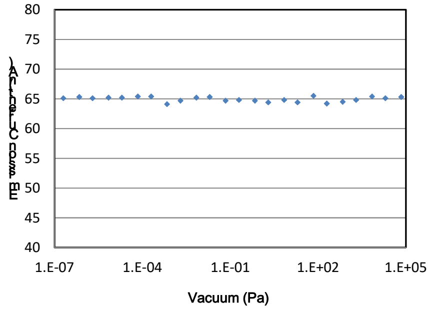

Fig. 3. Emission stability test in different vacuum

Since the device is expected to work below 10V, usually for a reason of avoiding gas discharge. An emission stability test with different vacuum is made at a fixed bias voltage of 8V. The result in Fig.3 shows that the emission current only has slight vibration, indicating the device has good vacuum environments adaptability.

Failure Analysis: Failure analysis of the device is also carried out. The device failures can be resulted from several reasons such as electrodes short, high temperature, strong electric field and chemical invasion, etc.

Excepting process defects, most electrodes short occurred in fabrication or in test are resulted from conductive particle adhesion, which comes from fabrication process or the abrupt and violent air flow, for example poor-controlled nitrogen filling process, therefore a stale and clean working circumstance is preferred.

High temperature can induce electrode deformation and layer peeling-off and consequent device failure. While in test, it has indicated the devices can endure 400 ℃ heating treatment and Joule heating resulted from several microampere emission current.

Strong electric field under low bias voltage give rise to electrode atom evaporation other than gas discharge. A overdrive test is carried out and it shows that the device can work at 50V without damage, so that 10V or lower bias is safe for the device.

Chemical invasion can change material work function and deteriorate the emission ability. Chemical stable Mo is preferred as the electrode material especially the source to fragile silicon in research.

Conclusion

Metal-electrode-based nanoscale vacuum channel transistors with vertical surround-gate configuration are fabricated. The emission ability and emission stability tests in different environments indicate the device has good vacuum environments adaptability. Possible reasons for device failures are analyzed. Future work is mainly focused on component performance improvement and long-term stability.

Acknowledgment

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