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〈연구논문〉

Emission Characteristics of MOS Electron Tunneling Cathode

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MOS 형태 전자 턴넬링 전극의 특성

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Abstract – Si-gate MOS electron tunneling cathode was fabricated and its emission characteristics were examined. The emission occurred from an entire gate area by electron tunneling through the potential barrier in the MOS diode and was stable in the Si-gate diode. The energy distribution of emitted electrons was measured and was confirmed to be mainly determined by the scattering process of hot electrons in the oxide and gate. The emission current from the tunneling cathode was nearly independent of pressure.

요　약 – 실리콘 gate의 MOS 전자 턴넬링 전극을 구성하여 그 특성을 조사하였다. 전자 방출은 전 gate 영역에서 MOS diode의 전위차를 지나는 턴넬링에 의하여 일어나고 안정하였다. 측정된 전류에서 산화막과 gate에서의 열전자의 충돌을 연구하였다. 방출된 전류는 압력에 관계없이 일정하였다.

1. Introduction

An electron tunneling emission cathode has the potential for high current density and pressure insensitivity of emission current and is a flat cathode in contrast with a field emission cathode. Due to these advantages, the tunneling cathode is a powerful candidate as a fine cathode for vacuum microelectronic devices.

We have fabricated an Al-gate and amorphous Si-gate MOS electron tunneling cathodes and have examined the emission characteristics. The emission current was given by the Fowler and Nordheim equation and the transfer ratio, i.e., the ratio of the emission current to the total current flowing through the MOS diodel, was 0.7%. The emission current was very stable in the Si-gate MOS cathode, in contrast with the Al-gate cathode. In addition, the current was nearly independent of pressure ranging from 10^{-8} to 10^{-1} torr.

2. Fabrication of MOS Tunneling Cathode

Fig. 1 shows the energy band diagram of the MOS electron tunneling cathode. When a voltage exceeding the work function of the metal electrode is applied, electrons tunnel through the potential barrier between the semiconductr and oxide, after they are accelerated by the applied electric field in the oxide, pass through the gate metal and finally some of them are emitted into vacuum.

Fig. 2 shows a schematic drawing of the Si-gate MOS cathode. An n-type Si wafer with a dopant concentration of $1\times10^{15}\,\mathrm{cm}^{-3}$ was oxidized to form thick SiO_2 by wet oxidation. After patterning the gate area, the Si surface was oxidized in dry O_2.

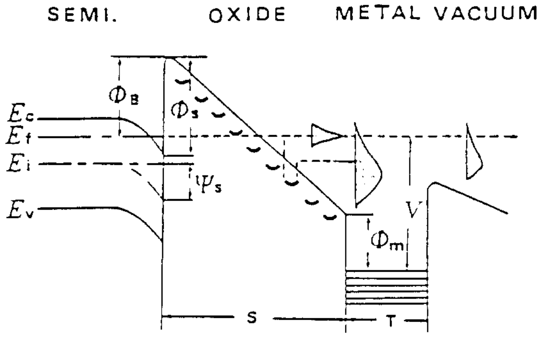


Fig. 1. Energy diagram of a MOS electron tunneling cathode.

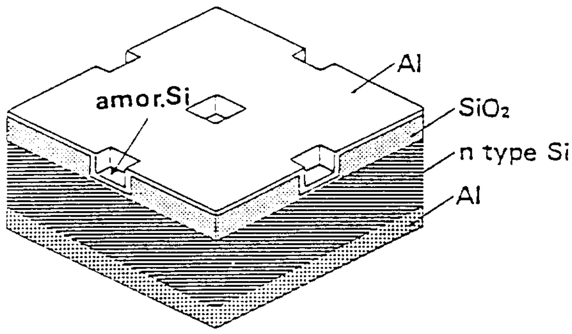
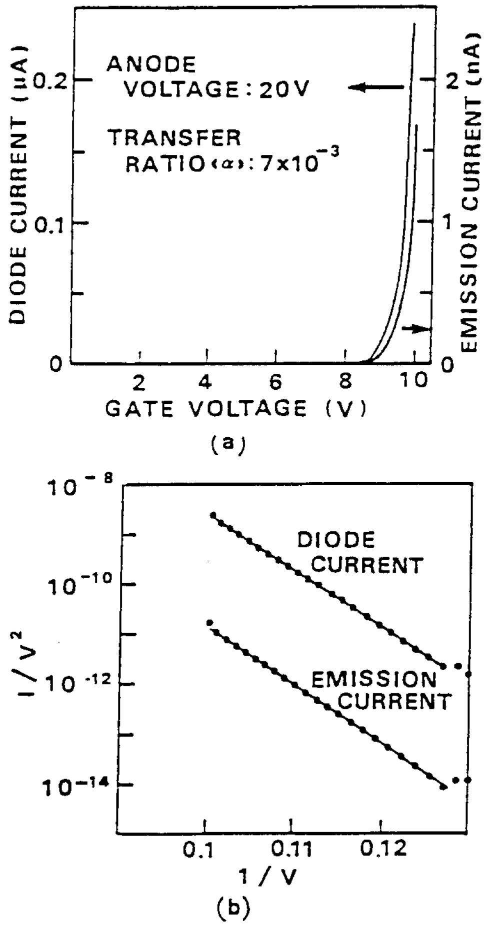


Fig. 2. Schematic drawing of a MOS tunneling cathode with a honeycomb structure.

The resultant oxide thickness of the gate area was determined to be 4~20 nm by ellipsometry and C-V measurements. An ultrathin Al-gate and an amorphous Si-gate with a thickness of 6~30 nm were deposited on the gate oxide by using ion energy-controlled bias sputtering method and low pressure chemical vapor deposition (LPCVD) of Si, respectively. Finally, Al electrodes were deposited on both sides by usual vacuum evaporation.

The paper presents experimental results obtained only from single MOS diodes with a gate size of 0.5 mm square to characterize reproducibility and stability of the cathodes. The experimental values of diode current agree well with the tunneling current calculated by the Wentzel-Kramers-Brillouin (WKB) approximation[1]. In addition, the current density-electric field intensity characteristics of tested diodes with different sizes and oxide thicknesses could be normalized to nearly the same trace, suggesting that the tunneling current flows uniformly through the entire gate area of the diodes.



(a)

(b)

Fig. 3. Diode and emission currents of a MOS tunneling cathode as a function of gate voltage (a) and its Fowler-Nordheim plots (b).

3. Emission Characteristics of MOS Cathode

Fig. 3(a) and (b) show the typical diode and emission currents of the cathode with an Al-gate thickness of 6 nm measured at a pressure of 10^{-6} torr, as a function of gate voltage and its Fowler-Nordheim plots, respectively. Both the currents have an exponentially increasing form, indicating that emission also occurs from the entire gate area by the electron tunneling through the potential barrier in the MOS diode. The transfer ratio α was about 0.7%, which is considerably higher than that of

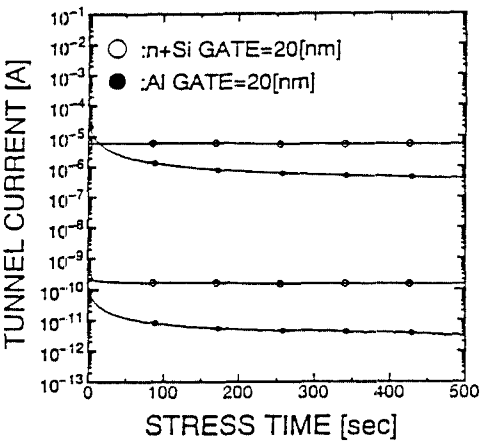


Fig. 4. Time dependence of the diode and emission currents of an amorphous Si-gate and an Al-gate MOS cathodes for a constant gate voltage.

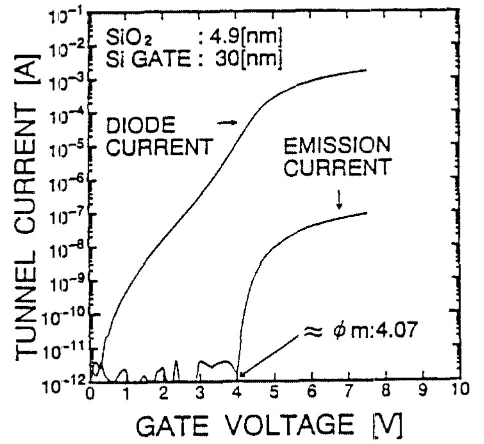


Fig. 5. Typical diode emission currents of a Si-gate MOS cathode as a function of gate voltage.

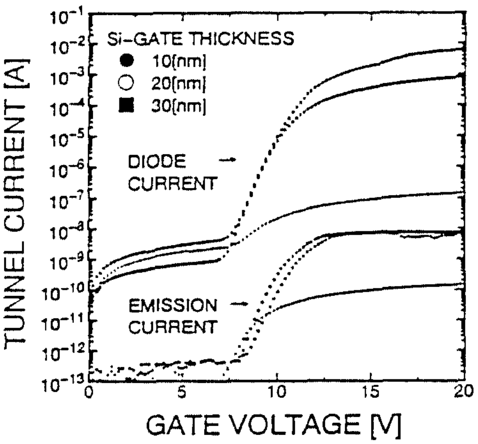


Fig. 6. Diode and emission currents for several cathodes with different thicknesses of Si-gate, as a function of gate voltage.

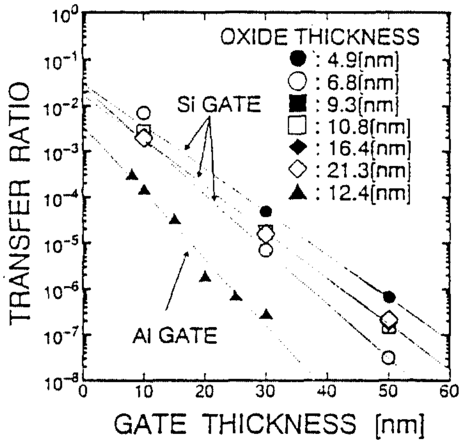


Fig. 7. Transfer ratios for Si-gate MOS cathodes with different oxide thicknesses and an Al-gate cathode, as a function of gate thickness.

MIM at high field and resulted in rapid reduction in emission current. Fig. 4 shows time dependence of the diode and emission currents of an Al-gate MOS cathode for a constant gate voltage comparing with that of an amorphous Si-gate cathode. Both the currents are very stable in a Si-gate cathode. Hereafter, we describe the emission characteristics of Si-gate cathodes.

Fig. 5 shows a typical characteristic of the cathode and emission currents for the diode with a Si-gate thickness of 4.9 nm and gate oxide thickness of 30 nm as a function of gate voltage. The emission occurred at nearly 4 V corresponding to the work function of Si-gate. The current saturation belongs to the series resistance effect in the thin Si-gate, which is clearly shown in Fig. 6. The figure shows the diode and emission currents for several cathodes with different thicknesses of Si-gate as a function of gate voltage. The currents of thinner diode saturate at lower gate voltage. Fig. 7 shows the transfer ratios for several cathodes with different thicknesses of the gate oxide, as a function of the thickness of Si-gate. Thickness dependence of the Al-gate is also shown in the figure. The effecitive

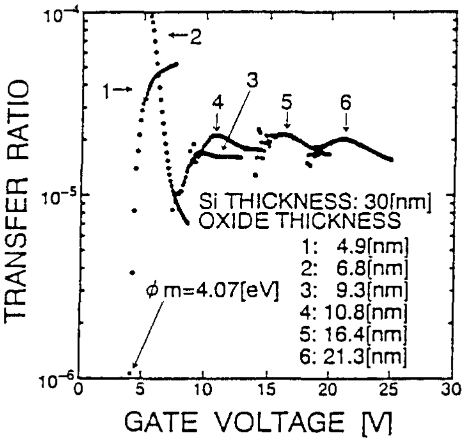
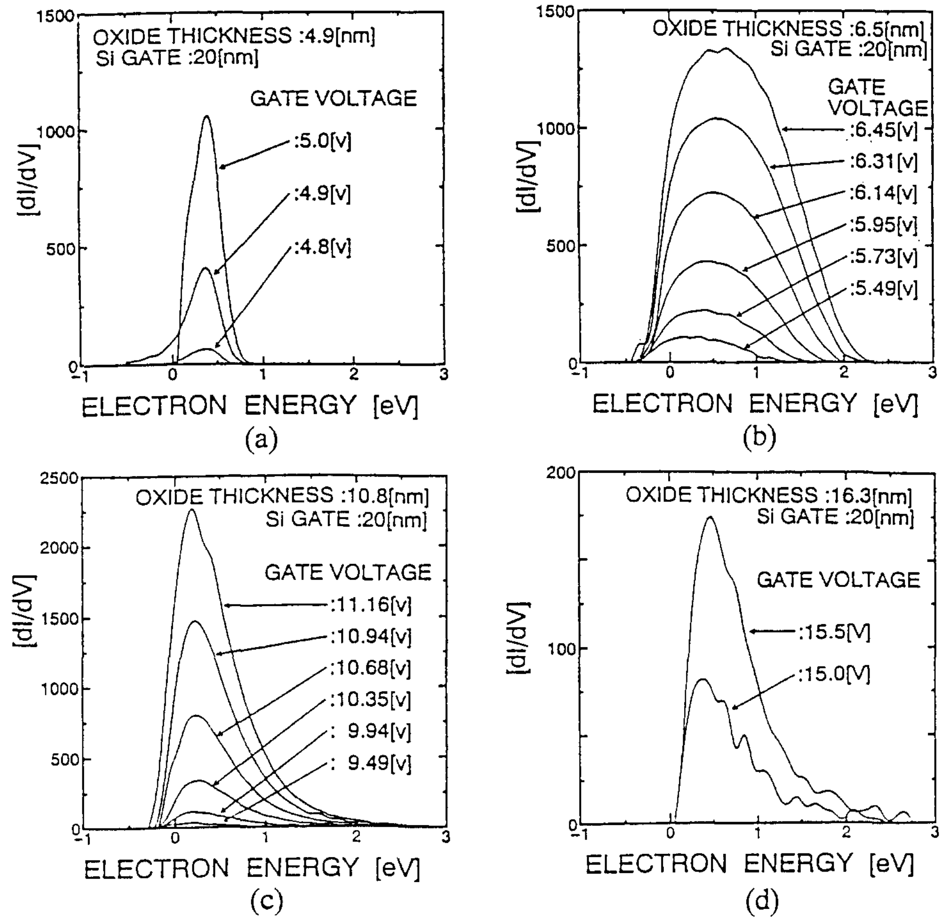


Fig. 8. Transfer ratios for several Si-gate cathodes with different thicknesses of the oxide, as a function of gate voltage.

mean free paths of hot electrons were evaluated as 4.4 nm in the Si-gate and 2.8 nm in the Al-gate, respectively. A Si is better as a gate material in MOS tunneling cathode than an Al, because longer mean free path of electrons in a gate provides higher transfer ratio for electron emission. However, when we extrapolate the slopes in the figure, the intersections at the gate thickness of zero do not reach unity and are a few % in the Si-gate and less in the Al-gate, respectively.

The experimental results show that a substantial role in the charge transport through thee oxide layer is played by the scattering process in the gate oxide. Fig. 8 shows the transfer ratios for several cathodes with different oxide thicknesses and a Si-



(a)
(b)
(c)
(d)

Fig. 9. Energy distribution of emitted electrons for Si- gate cathodes with oxide thicknesses of 4.9 nm (a), 6.5 nm (b), 10.8 nm (c), and 16.3 nm (d).

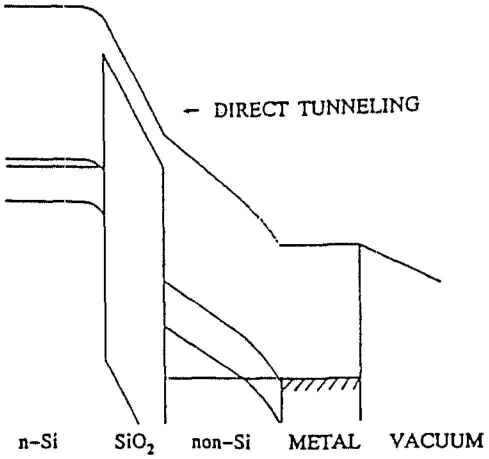


Fig. 10. New structure of electron tunneling cathode constructed with 4 thin layers.

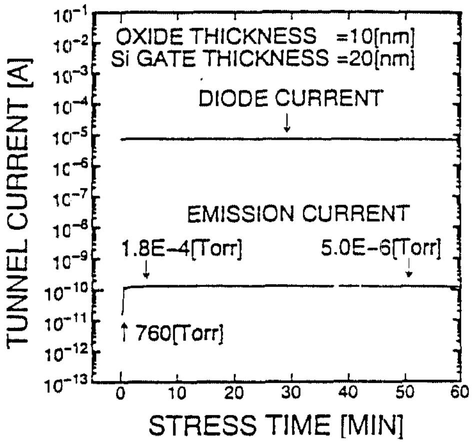


Fig. 11. Pressure dependence of emission current for a Si-gate MOS cathode.

gate thickness of 30 nm, as a function of gate voltage. Thinner in the gate oxide is higher in the transfer ratio for very thin gate oxide cathodes, but they become nearly same for relatively thick oxide cathodes at high field suggesting that the scattering process of hot electrons in the conduction band of the oxide is remarkable and makes a steady state energy distribution of electrons after traveling through the conduction band of the oxide.

We measured the energy distributions of emitted electrons to investigate above speculation. Fig. 9(a) to (d) show the energy distributions of electrons for the cathodes with respective oxide thicknesses of 4.9 nm to 16.3 nm. Half width of electron energy becomes wider corresponding to the gate voltage for thin gate oxide cathodes, as shown in Fig. 9(a) and (b). However, the half width becomes nearly constant for thick oxide cathodes above the oxide thickness of 10 nm, as shown the Fig. 9(c) and (d), and their absolute values are smaller than that of the thinner oxide cathode, shown in Fig. 9(b). The experimental results clearly support the previous speculation.

Following these experimental results, we proposed a new structure of tunneling cathode to increase the transfer ratio and to reduce the energy spread of emitted electrons. Fig. 10 shows an energy band diagram of the proposed cathode with 4th layers. Electrons tunnel directly through the oxide potential barrier without scattering, after which they are accelerated in the depletion layer of nondoped Si film, pass through a metal-gate or a Si-gate, and finally they are emitted into vacuum.

Additionally, we investigated pressure dependence of the emission current for the Si-gate MOS cathodes and confirmed that the emission current was nearly indenpendent of pressure and occurred even at atmospheric pressure. Fig. 11 shows the changes of the diode and emission currents by the pressure change. In the first place, the emission current was measured at the atmospheric pressure in a vacuum chamber. When the chamber was pumped down by a rotary and turbo-molecular pump system, several tenth seconds later, the pressure in the chamber may be several torr of several tenth torr, the emission current increased rapidly one order of magnitude and was nearly constant afterwards. The results clearly show that the electron emission from a tunneling cathode is nearly independent of pressure.

4. Conclusion

Electron emission due to electron tunneling thrugh the potential barrier in a MOS diode was investigated. The emission current is 0.7% of the total current flowing through the MOS diode and is correlated strongly with the scattering process of hot electrons in the oxide and gate. The emission current was stable in an amorphous Si-gate MOS cathode in contrast with an Al-gate cathode and was nearly independent of pressure over a range from 10^{-8} to 10^{-1} torr. Following the experimental results, a new structure of tunneling cathode is proposed to increase the tansfer ratio and to reduce the energy spread of emitted electrons.

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References

1. K. Yokoo, *et al.*, *J. Vac. Sci. Technol.*, **B11**, 1-4 (1993).