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Fowler-Nordheim current oscillations in Si(111)/SiO$_2$/twisted-Si(111) tunneling structures

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1. Introduction

Study on coherent nature of electrons in tunneling through SiO$_2$ is important in developing novel Si devices such as resonant tunneling devices and optical devices. More than two decades ago, Weinberg and Hartstein studied transverse momentum conservation in metal-oxide-semiconductor (MOS) structures for Fowler-Nordheim (FN) tunneling of electrons from Si with different orientations into thin SiO$_2$ [1]. However, the transverse momentum conservation was not found, and the result was attributed to the amorphous nature of SiO$_2$ and/or interface roughness. In this work, we attack this problem again by adopting new structures based on the wafer bonding technique, i.e., Si(111)/SiO$_2$/Si(111) structures, in which the two facing Si layers are intentionally misoriented with various twist angles. It is expected that, if the transverse momentum is conserved after tunneling through the SiO$_2$ layer, the potential discontinuity “seen” by the tunneling electrons at the SiO$_2$/collector-Si interface and consequently the reflectivity at this interface will depend on the twist angle. Change in reflectivity of electron wave leads to the change in the amplitude of Fowler-Nordheim current oscillations (FNCOs). In fact, we have found a systematic change in the amplitude of FNCOs as a function of the twist angle between the Si layers, indicating the conservation of transverse momentum.

2. Device structure

Thin SiO$_2$ (~3.5nm) was thermally grown on the top p-Si(111) layer of an SOI wafer, which was then bonded with an n$^+$-Si(111) wafer at room temperature in air intentionally misaligning the in-plane crystalline directions between the Si layers at various twist angles. After removing the Si substrate and the buried oxide layer of the SOI wafer, the top Si layer was n-doped, so that n-Si/SiO$_2$/n$^+$-Si structures were obtained (Fig. 1).

3. Results and discussion

In these structures, electrons tunnel from the emitter n$^+$-Si through the thin SiO$_2$ into the collector n-Si layer. Due to the twisted bonding, the constant energy ellipsoids in the two Si layers will be also twisted relative to each other at the same angle (Fig. 2).

FN tunneling occurs when the voltage drop in the oxide is larger than the potential of the barrier [2,3]. Consequently, electrons move in the conduction band of SiO$_2$. At the SiO$_2$/Si interface, electron waves will be partially reflected and will interfere with the incident electron waves, leading to FNCO. In the case of no misorientation between the Si layers, if the transverse momentum is conserved, the potential discontinuity and, according to the simple quantum theory, the reflectivity [4] at the SiO$_2$/collector-Si interface have maximum values (Fig. 3 (a)). On the other hand, in the structure with the twisted Si layers, in order to conserve their transverse momentum, tunneling electrons feel a decrease of the potential discontinuity at the SiO$_2$/Si interface. Therefore, the reflectivity at this interface for the twisted Si layers will be lower than for the aligned Si layers (Fig. 3 (b)).

Figure 4 shows the calculated ratio of the maximum transmission coefficient (T_{max}) to the minimum coefficient (T_{min}) for the twist angles between 0º and 30º. It can be observed that this ratio decreases with the increase of the twist angle, which provides the theoretical basis for the change in the amplitude of FNCOs.

FNCOs were extracted from the I-V characteristics, as shown in Fig. 5. For each twist angle, a number of devices were measured, and the average amplitudes of FNCOs are plotted. Figure 6 shows the twist angle dependence of the average amplitude of FNCOs. As expected, the largest amplitude is obtained when the two Si layers are aligned, while the lowest amplitude corresponds to a 30° twist angle between the Si layers. The periodicity of 60°, predicted under the transverse momentum conservation assumption, can be observed in our Si/SiO$_2$/twisted-Si structures.

4. Conclusions

The observed twist angle dependence of the amplitude of FNCOs confirms that the FN tunneling through thin SiO$_2$ maintains the transverse momentum of the electron waves. This result encourages us for developing novel devices using the coherent nature of tunneling electrons.

References

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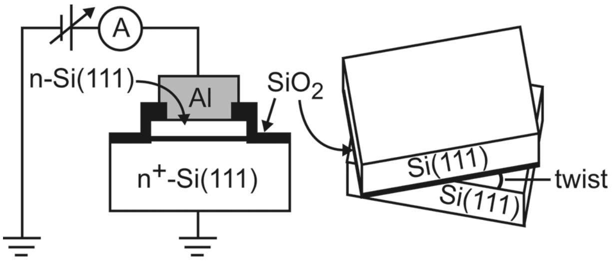

Fig. 1. Device structure and twist bonding of Si (111) wafers.

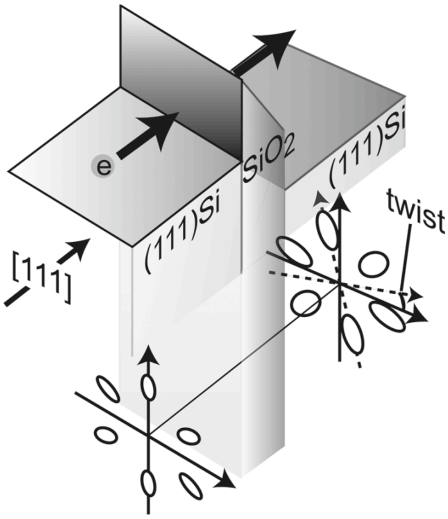

Fig. 2 Potential diagram of the structure with twisted Si layers.

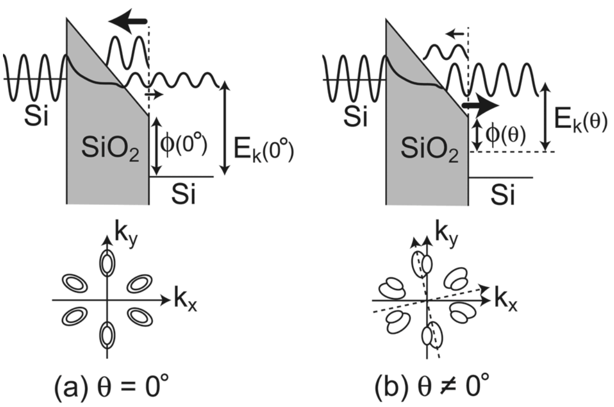

Fig. 3 Electron wave interference in the Fowler-Nordheim tunneling regime and constant energy ellipsoids for (a) non-twisted and (b) twisted Si layers.

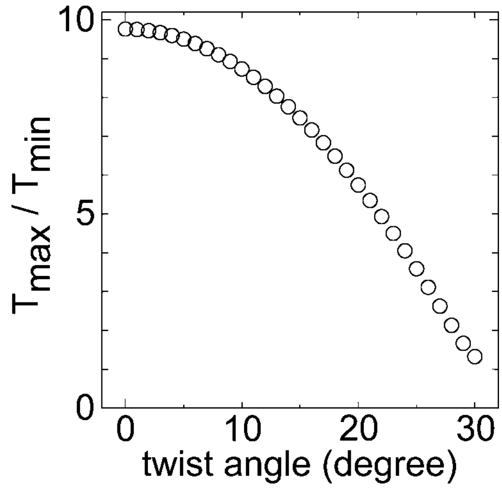

Fig. 4 Calculated twist angle dependence of ratio of the maximum transmission coefficient T_{max} to the minimum coefficient T_{min}.

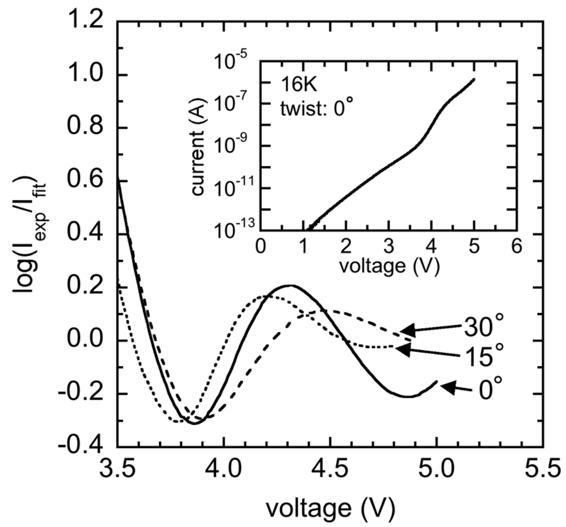

Fig. 5 Decrease of the FNCO amplitude with the twist angle (inset: typical I-V characteristics).

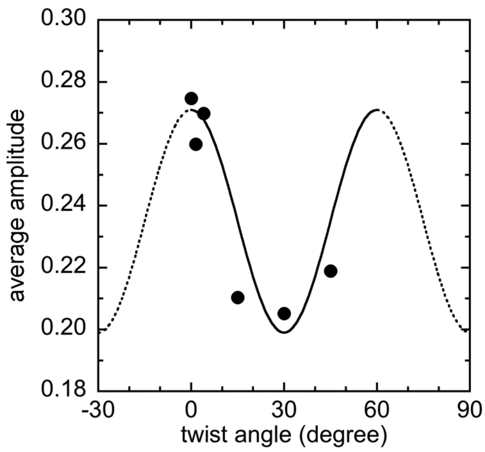

Fig. 6 Twist angle dependence of the average FNCO amplitude.