High negative differential resistance in silicon quantum dot metal-insulator-semiconductor structure

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Metal-insulator-semiconductor structures, comprised of silicon quantum dot films grown by plasma-enhanced chemical vapor deposition, were fabricated on Si wafers. The devices showed a negative differential resistance, as a result of the resonant tunneling and the very high peak-to-valley current ratios of 2240 under illumination and 390 in the dark at room temperature, which are much higher than the corresponding values of other Si tunneling devices. The peak voltage was reduced down to 1.9 V by increasing the doping concentration of the wafer and reducing the device area. The structure shows promise for use in solid-state switch applications. © 2006 American Institute of Physics. [DOI: 10.1063/1.2360888]
of a Si wafer process. The carrier tunneling from the Si wafer through Si film without Si QDs was grown during the initial QD growth in the samples because a few nanometer thick silicon nitride the wafer side of the Si QD than on the top nickel metal side complex structure. The barrier width appears to be thicker on QDs with asymmetric barriers, which demonstrates their connected in series in one current path. Figure 1 shows three multiple QD structure, we can consider that QDs are connected in series in one current path. For a n-type Si wafer, the conduction band or valence band edge of the Si wafer would rise up under a forward bias. Therefore, electron tunneling occurs. Although a theoretical investigation of resonant tunneling through multiple QDs shows the sharper peak current than other RTD structures, our results show that the peak current is broad over a wide range of voltage. This is due to fluctuations in the size of the dots in the multiple dot states that cause a small shift in the bound state level of the dots. Nevertheless, the peak-to-valley current ratio of 76 is much larger than the previously reported value of 4 for a Si system. Hole resonant tunneling can also occur, which could be observed in a reverse bias at $-5.5\,\text{V}$, as shown in the inset of Fig. 2(b). Hole tunneling current is observed to be much smaller than electron one due to the small mobility of hole.

When a p-type Si wafer ($1-10\,\Omega\,\text{cm}$) was used, the current peak was observed at $9.7\,\text{V}$ in a forward bias, as shown in Fig. 3 (black line). In this case, the valence band edge goes down and hole tunneling occurs. Electron tunneling was clearly observed at $-7.7\,\text{V}$ for a reverse bias. The negative resistance could also be due to transient current from the charging effect, in which charged QDs screen the applied field, preventing a current flow, resulting in a current dip (negative resistance). This is similar to the negative resistance from resonant tunneling. In the case of a charging effect, the same carriers as those charged in QDs, however, do not flow through the QDs and, as a result, the current dips more sharply when the carriers are charged in QDs. To further investigate the origin of the negative resistance in our samples, we charged Si QDs by generating carriers with a tungsten-halogen lamp (20 W) and measured the photocurrent characteristics. This is shown as a red line in Fig. 3. Si QDs in silicon nitride films are charged with electrons because of nitrogen dangling bonds at the dot surface. Therefore, if the negative resistance is related to the charging effect in our samples, the current dip must be sharper than the dark case and the PVCR must increase in a reverse bias under illumination because the electron charging prevents electron tunneling. However, the result appears to be the opposite. Therefore, the negative resistance in our samples is related to resonant tunneling. The absence of a current peak in the

![Graph showing current-voltage characteristics](image1)

![Graph showing current-voltage characteristics](image2)

**FIG. 2.** Current-voltage characteristics of (a) a normal silicon nitride film and (b) a Si QD MIS device. Both films were grown on a n-type Si wafer ($0.1-1\,\Omega\,\text{cm}$). Negative resistance by electron tunneling is observed only in the Si QD MIS device, in which the PVCR is about 76 at 7.2 V at room temperature.

**FIG. 3.** (Color online) Current-voltage characteristics of a Si QD MIS device grown on a p-type Si wafer ($1-10\,\Omega\,\text{cm}$). The PVCR is about 2240 at 9.7 V under conditions of illumination with a 20 W lamp at room temperature. In a reverse bias, the negative resistance disappeared when illuminated due to the field screening effect from electron charging in the Si QDs.
voltage due to the reduction in series resistance. Therefore, device area causes the peak current to be shifted to a lower value.

The peak current is also increased about one order of magnitude, compared with the sample on a low doped wafer shown in Fig. 3. A hole tunneling device has the advantage of fabricating a simpler logic for the given function than electron one. The high PVCR and low peak voltage also provide the potential for the system to act as a solid-state switch, but there is room to improve performance even more.

In summary, the results effectively demonstrate the preparation of a Si-based tunneling device using Si QD films at room temperature, with a peak-to-valley current ratio of 2240 under the illumination condition. Such functional electronic devices satisfy the required factors needed for miniaturization, multiplicity, and low manufacturing cost in silicon ultra-large-scale integration technology in the future.

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