Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp1290-1291

# Thermal stability of germanium quantum dots phototransistors for near ultra-violet applications

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## 1. Introduction

Integration of high-speed photodetectors and amplifiers in silicon CMOS-compatible processes has being pursued for developing low-cost and high-performance monolithic receiver for communication and chip-to-chip interconnects. Phototransistors (PTs) with planar structures such as thin-film transistors (TFTs) are a type of optical transducer in which light detection and signal amplification are combined in a single device without the associated noise increment, high bias voltages, and high cost, due to the potential for large area integrated circuits. Besides, demands for low cost and high sensitivity ultraviolet (UV) sensors are increasing for applications from the civil and environmental concerns.

The authors have reported that nanometer-scaled Ge quantum dots (QDs) formed by thermally oxidizing SiGe alloy exhibit conspicuous visible blue to near ultraviolet (UV) light absorption in the cathodoluminescence spectra. Accordingly, MOS photodetectors and PTs with Ge QDs embedded in the gate oxide were demonstrated to exhibit amplified photo-responsivities and quantum efficiency (~250 %) in the incident light wavelengths of 350-550 nm for near UV detection. The fabrication of Ge-QD PTs is fully CMOS compatible and therefore is easy to be embedded in the Si integrated circuits. These results strongly motivate detailed exploration on the thermal and time stability of Ge QDs PTs for practical applications on visible to near UV photodetection and amplifications. Thermal stability of a-Si and poly-Si TFTs has been extensively studied. In this article, we focused on studying of thermal and time stability as well as associated mechanisms on Ge-QDs poly-Si PTs, in contrast to conventional poly-Si PTs.

## 2. Experimental procedures

Figure 1 summarizes the key device fabrication process and schematic of double-gated Ge-QD poly-Si TFTs. Cross-sectional transmission electron microscopy examination shows that discrete Ge QDs are embedded in the top-gate oxide stack, and their size and spatial density are 3.62 ± 0.94 nm and 8.2 × $10^{10}$ $cm^{-2}$, respectively. The light was illuminated from the top side of the device through the transparent ITO electrode, corresponding to the opposite side of the Si substrate as the bottom-gate electrode.

## 3. Results and discussions

Drain current measured under 405 nm light irradiation of 1 mW at 300 K exhibits ~80 % enhancement for PTs with Ge QDs as compared with that measured in darkness for a given gate drive. In contrast, their counterpart PTs without Ge QDs incorporation has a photo-current enhancement of 25 % under the same light illumination and gate drive conditions. The intensity of drain current changed with the incident light power, which clearly follows from the contribution of photo-generated carriers. This phenomenon indicates that light can provide additional terminal to modulate the drain current.

Figure 2 shows measured temperature-dependent $I_d$ - $V_g$ characteristics of PTs with and without Ge QDs in darkness and under light illumination, respectively. For PTs without QDs measured in darkness, it is as expected that subthreshold slope (*SS*) reduces but threshold voltage ($V_{th}$) increases with progressively decreasing temperature, owing to reduced intrinsic carrier concentration at low temperature. Under light illumination, photo-generated holes contribute excess conducting carriers in the active channel in addition to thermal generation, resulting in $V_{th(\text{ photo})}$ less than $V_{th(\text{dark})}$, and their population keeps invariant with temperature. Suppressed $V_{th}$ spread with respect to temperature change ($\Delta V_{th}/\Delta T$) is a consequence of photo-generated holes population becoming comparable with the intrinsic carriers by thermal generation or even dominant in the channel at $T \leq 210$ K. However, the improvement of *SS* with decreasing temperature is hindered by photo-excitation due to photovoltaic effect, arising from the fact that photo-generated electrons accumulating near the source/channel junction lowers junction barrier height and in turn

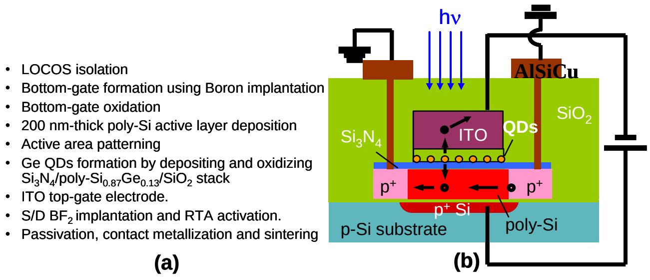


Fig. 1 (a) Process flow and (b) schematic of fabricated Ge-QD poly-Si PTs.

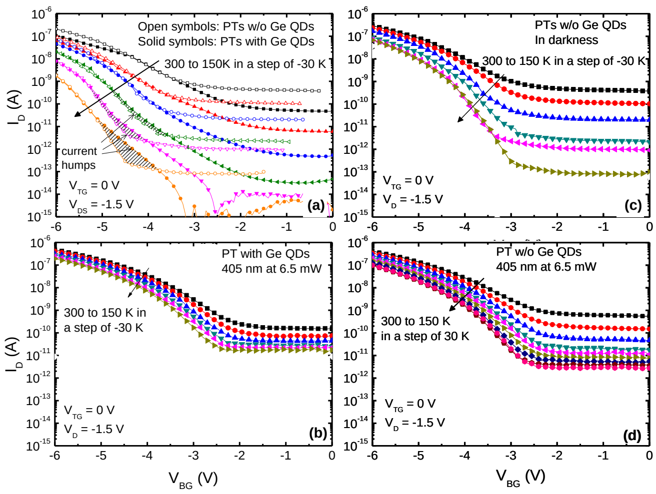


Fig. 2. $I_d$ - $V_g$ characteristics of PTs (a), (b) with and (c), (d) without Ge QDs measured, respectively, in darkness and under 405 nm light illumination. Each individual current curve of PTs withouts QDs in (c) at corresponding temperature is inset into (a) and shifted horizontally for clarifying the presence of current humps at low $V_{gs}$. The voltage shift increases as temperature decreases with -0.3 V, -0.65 V, -0.72 V, -0.95 V, -1.1 V, and -1.5 V, respectively, at 300 K, 270 K, 240 K, 210 K, 180 K, and 150K.

results in subthreshold leakage. The peculiarity of temperature-dependent subthreshold behaviors of Ge-QD PTs in darkness is the presence of additional current humps at low $V_{gs}$ and $T \leq 210$ K as well as the relatively substantial temperature-induced $V_{th}$ spread. This might originate from the fact that holes tunnel from the active layer into QDs within the top-gate dielectric before the channel turns on ($V_{gs} << V_{th}$). Positive charges storage within QDs leads to a negative $V_{th}$ shift, which becomes more evident at low temperature since a tunneling process is less temperature dependent. Under light irradiation, Ge-QD PTs exhibit significant improved *SS*, reduced $V_{th(\mathrm{photo})}$, and suppressed $\Delta V_{th} / \Delta T$ than those in darkness. This is inferred resulting from the fact that light absorption mainly occurs in QDs, and only photo-generated holes are injected into the active layer from QDs, but their counterpart photo-excited electrons are confined within QDs or injected into the top-gate electrode. Consequently, not only a much manifest $V_{th}$ reduction ($\Delta V_{th} \equiv | V_{th\ (\mathrm{photo})} - V_{th\ (\mathrm{dark})}|$) but also a significant *SS* improvement in Ge-QD PTs are a result of substantial excess hole contribution from QDs, which is in contradiction with the photovoltaic effects. Figure 3 shows that Ge-QD PTs exhibit remarkably better thermal stability in subthreshold characteristics (both *SS* and temperature-induced $V_{th}$ spread) than PTs without QDs under the same light illumination conditions. Again, efficient light absorption in QDs contribute excess hole generations in the conducting channel and the photoconduction is less temperature dependent, leading to better thermal stability in Ge-QD PTs.

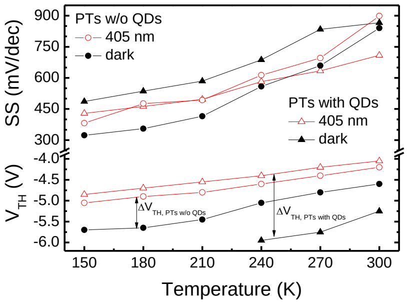


Fig. 3 *SS* and $V_{th}$ of PTs with and without QDs as a function of temperature, respectively, in darkness and under 405 nm light illumination.

Figure 4 compares the transient drain current behaviors of PTs with and without Ge QDs in response to light pulse modulation. Long time-scale drain current behaviors of PTs measured under light illumination and in darkness are plotted as references. Photo- and dark currents of both PTs keep nearly invariant with time, evidencing the devices stability in steady state. Figure 4(a) shows that the drain current of PTs at room temperature exhibits distinct two-level states as light pulses are switched on and off. After consecutive light-pulse cycles, Ge-QD PTs well retain their steady-state photo-current level as light pulses turn on, but could not restore to their initial dark current level gradually as light pulses are off. PTs without Ge QDs show opposite trends in the photo- and dark currents in the endurance test. The dark current restores well to the steady-state current level as light turns off, but the photo- current gradually decreases after repeated light pulses modulation. The comparatively fast turn-on ($t_{rise}$ = 0.5 msec) and slow turn-off ($t_{fall}$ = 2.4 msec) behaviors of Ge-QD PTs indicates that generation (injection from QDs to the channel) and release (recombination in the channel) speeds of holes in the channel are asymmetrical. The rise time ($t_{rise}$) and fall time ($t_{fall}$) are defined as the time required for current changing from its initial value to final

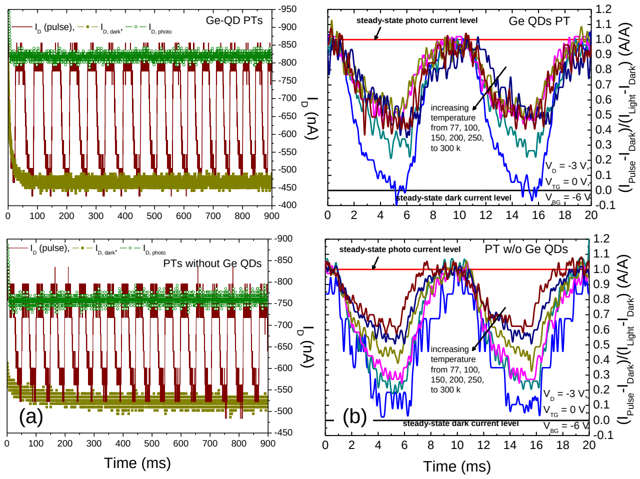


Fig. 4 (a) room temperature and (b) temperature-dependent transient $I_d$ behaviors of PTs with and without Ge QDs, respectively, in response to light pulse modulation.

value (10% - 90%), respectively. Such asymmetrical transient behaviors stem from the fact that light absorption process occurs predominantly in QDs embedded in the top-gate dielectrics, leading to merely photo-generated holes injection into the active channel via vertical electric field, but without the company of photo-generated electrons. Consequently, excess holes could not recombine with native minority carriers in the channel expeditiously as the light was turned off. In contrast, electron/hole pairs are photo-generated in the channel simultaneously for PTs without QDs, so that excess holes could recombine with their photo-generated companion or native electrons as the light is off, leading to nearly symmetrical turn-on ($t_{rise}$ = 1 msec) and turn-off ($t_{fall}$ = 1.4 msec) behaviors. Ge-QD PTs having relatively fast rise time than PTs without QDs indicates better light absorption efficiency in QDs than in a poly-Si layer, which supports the results in Fig. 3. Figure 4(b) compares temperature-dependent (300-77 K) transient current responses of PTs with and without QDs with respect to light pulses. Both PTs lose their restoring ability to their initial dark current level as temperature decreases, and such phenomenon is much exacerbated in PTs without Ge QDs.

## 4. Conclusion

The study of temperature-dependent subthreshold behaviors and transient current of Ge-QD PTs in response to light modulation indicates that incorporating QDs into TFT or MOSFET structures can significantly improve not only the photoconductivity, but also the thermal stability and transient responsivity. This originates from superior light absorption efficiency in QDs than in a bulk layer and suppressed photovoltaic effects. In fact, Ge-QD PTs is not limited to near UV detection and amplification, but could be applied for other wavelength light detection and amplification by incorporating different size QDs into the gate dielectrics according to quantum confinement effects. The QD size could be tuned by modulating oxidation time and Ge content in $Si_{1-x}Ge_x$ during thermal oxidation of SiGe.


## Acknowledgements

This work was supported by the National Science Council of R. O. C. under Contract No. NSC 97-2120-M-008-002.