1/*f* noise in *n*-channel metal-oxide-semiconductor field-effect transistors under different hot-carrier stresses

J. P. Xu, P. T. Lai,[a] and Y. C. Cheng
Department of Electrical and Electronic Engineering, the University of Hong Kong, Pokfulam Road, Hong Kong

(Received 8 June 1999; accepted for publication 19 July 1999)

Degradation mechanisms contributing to increased 1/*f* noise of *n*-channel metal-oxide-semiconductor field-effect transistors (*n*-MOSFETs) after different hot-carrier stresses are investigated. It is demonstrated that for any hot-carrier stress, the stress-induced enhancement of 1/*f* noise is mainly attributed to increased carrier-number fluctuation arising from created oxide traps, while enhanced surface-mobility fluctuation associated with electron trapping at preexisting and generated fast interface states and near-interface oxide traps is also responsible under maximum substrate- and gate-current stresses. Besides thermal-oxide *n*-MOSFETs, nitrided-oxide devices are also used to further support the above analysis. © *1999 American Institute of Physics.*
[S0021-8979(99)00521-6]

I. INTRODUCTION

As the gate length of metal-oxide-semiconductor field-effect transistors (MOSFETs) is shrunk to submicrometer dimensions in recent years, 1/*f* noise of MOSFET increases, and becomes an important reliability issue which attracts much research interest.[1–4] Moreover, it is found that 1/*f* noise is very sensitive to hot-carrier stresses[5–7] and can be increased to different extents for different hot-carrier stresses.[8,9] In this work, it is found that the stress-induced increase of noise can be partly recovered after a short injection of electrons or holes, revealing different noise-degradation mechanisms for different hot-carrier stresses. Moreover, it is shown that the relative contribution of mobility fluctuation to the increase of 1/*f* noise depends on the extent of electron trapping at fast interface states and oxide traps very close to the interface. These observations provide strong evidence for a trap-charge fluctuation model incorporating both the number fluctuation and surface-mobility fluctuation mechanisms.[10–12] Detailed discussions on the involved mechanisms are made for both thermal-oxide and nitrided-oxide devices, while the latter exhibiting considerably suppressed degradation of 1/*f* noise. As a result, some new insights on trap generation at or near the oxide/Si interface under different hot-carrier stresses are obtained.

II. EXPERIMENTS

The *n*-channel MOSFETs used in this study were fabricated on *p*-type (100) silicon wafers with a resistivity of 6–8 Ω cm by a self-aligned n^+ poly silicon gate process. After the channel region was implanted by B^+ through a sacrificial oxide which was then stripped, thermal gate oxide (OX) was grown at 850 °C for 70 min in dry O_2. N_2O-nitrided oxide (N2ON) was obtained by annealing a thinner thermal oxide (grown at 850 °C for 60 min in dry O_2) at 950 °C for 20 min in pure N_2O ambient so as to achieve the same thickness. The two gate oxides were finally annealed in N_2 at 950 °C for 25 min. Final thickness measured by capacitance−voltage ($C-V$) technique was about 160 Å for both oxides. Hot-carrier stresses with maximum substrate current I_{Bmax} at $V_D=2V_G=7$ V, maximum gate current I_{Gmax} at $V_D=V_G=7$ V or low V_G ($V_D=7$ V, $V_G=0.2$ V) were, respectively, carried out to investigate the degradation mechanisms of 1/*f* noise. The 1/*f* noise was characterized by the noise power (S_{id}) of drain current which was derived from a unified 1/*f* noise model of incorporating both number fluctuation and surface mobility fluctuation.[12] S_{id} was measured using a HP 35665A dynamic signal analyzer, BTA 9603 FET noise analyzer and HP 4145B semiconductor parameter analyzer in the linear region of device operation ($V_D=0.2$ V) for a gate overdrive voltage $V_G^*=V_G-V_T=0.5$ V (V_T is the threshold voltage) at a frequency of 30 Hz. The number of averages used in the noise measurement system was 80. The variation between repeatedly measured data on a single transistor was less than 10% and the final value was averaged over these data. The sample size was 4. The used channel length L and width W of the devices were 1.2 and 24 μm, respectively.

III. RESULTS AND DISCUSSION

A. Maximum substrate-current stress

Figure 1 shows the percentage degradations of noise properties (ΔS_{id}) and peak linear transconductance (ΔG_m) for *n*-MOSFETs after I_{Bmax} stress for different times (I_{Bmax} changing from 12.1 to 11.5 μA/μm). The prestress S_{id} and G_{m} are, respectively, 8.7×10^{-20} A^2/Hz and 28 μS for the OX sample, 1.1×10^{-19} A^2/Hz and 27 μS for the N2ON sample. Similar to the results in Ref. 13, the degradation of 1/*f* noise is much faster than that of transconductance, and ΔS_{id} is one to two orders of magnitude larger than ΔG_m.

Interestingly, it is found that after I_{Bmax} stress, ΔS_{id} and ΔG_m can be recovered to some extent through hole injection at $V_D=7$ V and $V_G=0.2$ V, as shown in Fig. 2. ΔS_{id} first

[a]Electronic mail: laip@hkueee.hku.hk

 © 1999 American Institute of Physics

Downloaded 03 Nov 2006 to 147.8.21.97. Redistribution subject to AIP license or copyright, see http://jap.aip.org/jap/copyright.jsp

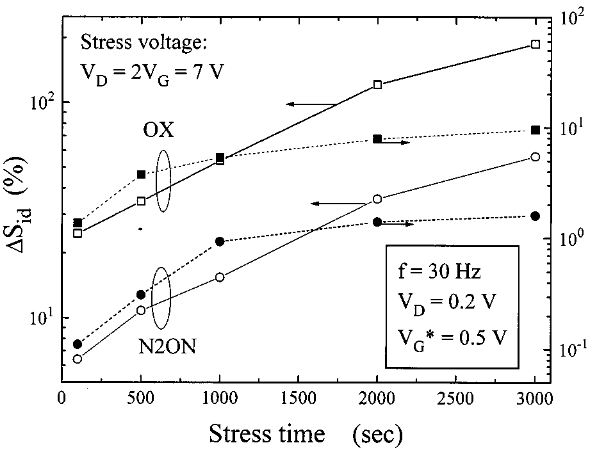

FIG. 1. Degradations of drain-current noise power and peak linear transconductance under I_{Bmax} stress ($V_D = 2V_G = 7$V) as a function of stress time.

decreases and then increases after a 100 s hole injection. In order to explain the phenomena, it is necessary to understand the following facts: (1) during I_{Bmax} stress, both electrons and holes are injected into the gate oxide close to the interface and when a trapped hole recombines with an electron, an oxide or interface trap is generated;[14] (2) according to McWhorter's number-fluctuation model,[15] it is strongly believed that $1/f$ noise originates from oxide traps[16] and its degradation should be proportional to an increase of oxide-trap density around the electron quasi-Fermi level. Moreover, oxide traps contributing to $1/f$ noise are those lying within a window near the quasi-Fermi level as shown in Fig. 3,[17] since traps located at $x < x_1$ (for convenience, hereafter named as interfacial oxide traps) fluctuate too quickly, while traps located at $x > x_2$ fluctuate too slowly to be detected in the frequency range of a typical noise measurement. However, the interfacial oxide traps and fast interface states also seem to impose their effects on $1/f$ noise in the Coulombic scattering form; (3) hole injection is conductive to the detrapping of trapped electrons due to a lowering of the electron quasi-Fermi level under this injection condition. Therefore, the recovery should eliminate the effects of electron

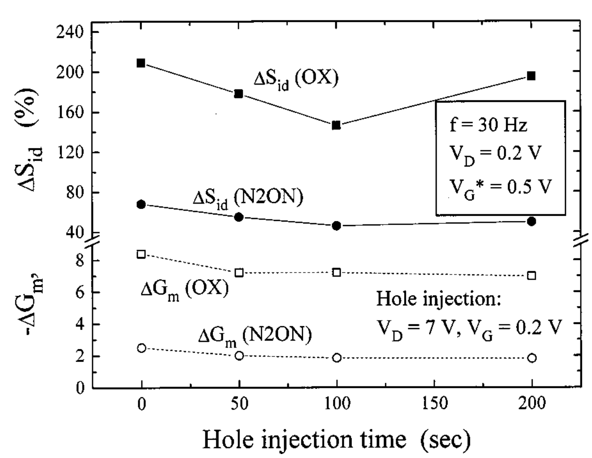

FIG. 2. Recoveries of ΔS_{id} and ΔG_m with hole injection after a 3000 s I_{Bmax} stress at $V_D = 2V_G = 7$ V.

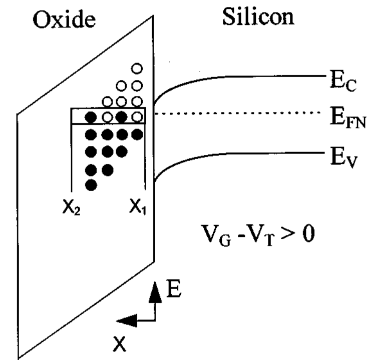

FIG. 3. Schematic diagram of oxide-trap window detectable by a measurement of $1/f$ noise in (x,E) space (E is the energy level of oxide traps).

trapping near the interface and the corresponding traps should be located at $x < x_1$, i.e., the interfacial oxide traps and fast oxide/Si interface states. Otherwise, they would increase $1/f$ noise through larger carrier-number fluctuation after hole injection. In detail, preexisting and newly created interfacial oxide traps and fast interface states could be charged by injected electrons during I_{Bmax} stress. Although their number fluctuation cannot be probed by $1/f$ noise measurement, these charged traps could give rise to Coulombic scattering to carriers in the channel due to their closeness to the conduction channel, and thus the mobility of the carriers is affected. This argument is further supported by the following observations: (1) as V_G increases, recovery of ΔS_{id} decreases; (2) after ΔS_{id} decreases to a minimum at the end of a 100 s hole injection, a 20 s electron injection at $V_D = V_G = 7$ V can rebound ΔS_{id} close to its initial value. The first observation is due to a reduction of vertical field used for hole injection at a higher V_G, resulting in fewer holes injected into the oxide, and thus a smaller recovery of ΔS_{id}. The second observation involves substantial charging and discharging effects of the traps, and the decrease or increase of ΔS_{id} can occur repeatedly as hole or electron injection is alternately performed. Therefore, from the maximum ΔS_{id} at zero injection time and the minimum ΔS_{id} at 100 s injection time in Fig. 2, it can be roughly estimated that the increase of $1/f$ noise arising from mobility fluctuation is about 30% and 32% of total ΔS_{id}, respectively, for the OX and N2ON samples. Slightly larger recovery for the N2ON sample might be due to more preexisting interfaces states and interfacial oxide traps associated with the N_2O nitridation, as confirmed by charge-pumping (CP) measurement (the two are indistinguishable in CP measurement, with average values of 3.0×10^{10} $cm^{-2} eV^{-1}$ for the OX sample and 7.5×10^{10} $cm^{-2} eV^{-1}$ for the N2ON sample), since the stress-induced increase of interface-state density is much smaller in the N2ON oxide (2.7×10^{10} $cm^{-2} eV^{-1}$) than in the OX oxide (6.4×1010 $cm^{-2} eV^{-1}$) after a 3000 s stress.

A ΔS_{id} turnaround after an injection time of 100 s in Fig. 2 is probably ascribed to detrapping of the oxide traps located within the window shown in Fig. 3, and/or the generation of new oxide traps, and thus increasing the probability of carrier exchange in subsequent $1/f$ noise measurement. Since MOSFET static parameters (e.g., G_m) are mainly affected by interface trap (fast states),[18] ΔG_m keeps decreasing

Downloaded 03 Nov 2006 to 147.8.21.97. Redistribution subject to AIP license or copyright, see http://jap.aip.org/jap/copyright.jsp

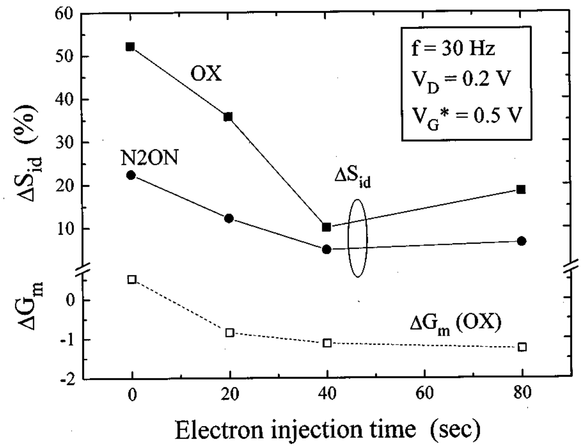

FIG. 4. Degradations of S_{id} and G_m after a 3000 s low-V_G stress ($V_D=7$ V, $V_G=0.2$ V) and their changes with a subsequent electron injection at $V_D=V_G=8$ V.

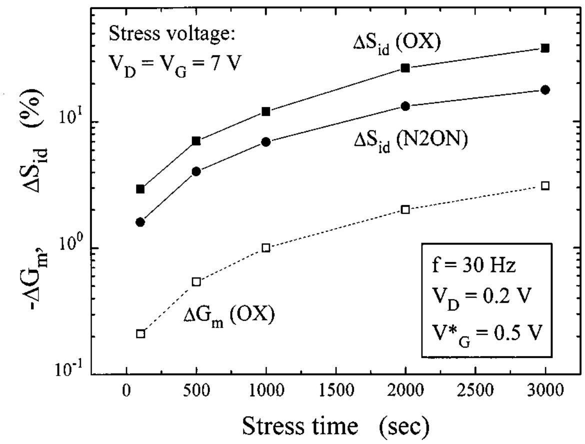

FIG. 5. Degradations of S_{id} and G_m under I_{Gmax} stress ($V_D=V_G=7$ V) as a function of stress time.

with hole injection. Based on the above discussions, it can be suggested that the measurement window of $1/f$ noise in Fig. 3 actually exists, and leads to I_{Bmax} stress-induced degradation of $1/f$ noise being a combined effect of carrier-number and surface-mobility fluctuations, with the former dominating. It is especially worth pointing out that the degradations are greatly suppressed for the N2ON sample due to hardened oxide and oxide/Si interface resulting from N_2O nitridation, as illustrated in Figs. 1 and 2.

B. Low-V_G hot-hole stress

Figure 4 shows ΔS_{id} and ΔG_m after a low-V_G hot-hole stress ($V_D=7$ V and $V_G=0.2$ V) for 3000 s (the points at zero injection time) and their subsequent changes with electron injection at $V_D=V_G=8$ V. It can be seen that for the OX sample, although G_m exhibits a small increase after the hot-hole stress due to the channel-shortening effect caused by hole trapping in the gate oxide located near the drain junction,[19,20] a large degradation of $1/f$ noise is still observed due to the generation of neutral electron traps during the stress. Most of the neutral electron traps should lie in the vicinity of the interface because the injected holes are unable to penetrate deep into the oxide.[21] This fact means a higher change of channel-carrier fluctuation, and hence a larger ΔS_{id}. Interestingly, subsequent electron injection shifts ΔS_{id} to a smaller value and at the same time ΔG_m to a negative value. This is attributed to the compensation of trapped holes and filling of neutral electron traps by injected electrons, thus decreasing carrier-number fluctuation. Similar to I_{Bmax} stressing, when a 200 s hole injection follows the electron injection, the reduced ΔS_{id} rebounds to about the maximum value due to increasing carrier-number fluctuation. Therefore, under stress conditions with less electron injection, carrier-number fluctuation should be the dominant degradation mechanism of $1/f$ noise. The increase of ΔS_{id} after 40 s of electron injection is most probably due to the generation of oxide traps by electron injection because there is no detrapping effect of electron traps in this case. Of course, part of the increased ΔS_{id} could result from enhanced Coulombic scattering due to detrapping of hole traps and filling of neutral electron traps located at $x<x_1$ by increasing electron injection. For the N2ON sample, although G_m hardly changes, a ΔS_{id} smaller than that of the OX sample and a change with electron injection similar to that of the OX sample are still clearly observed in Fig. 4. This, once again, indicates that $1/f$ noise measurement is indeed a very sensitive tool to probe the damages in gate oxides, even though the damages are very small.

C. Maximum gate-current stress

Presented in Fig. 5 are degradations of $1/f$ noise and G_m under maximum gate-current stress ($V_D=V_G=7$ V) as a function of stress time ($I_{Gmax}=10.4$ pA–11.2 pA/μm). ΔS_{id} is the smallest as compared to those under the previous two stresses. The change of G_m for N2ON sample is too small to be shown. This further demonstrates that G_m suffers mainly from fast interface states, since the stress mainly creates oxide traps.[22] Moreover, it can be believed that most of the created traps are located at positions farther from the interface than those created by the previous two stresses due to a higher electron-injection field and the higher mobility of electron than that of hole in SiO_2. So, the smaller effect on S_{id} is reflected under the same noise measurement conditions (the same detecting window). However, the degradation would increase as a result of applying heavier stress at $V_D=V_G=8$ V for 3000 s (I_{Gmax} from 15.8 pA/μm of starting to 14.6 pA/μm of ending), as shown in Fig. 6. Different change in G_m is observed for the OX and N2ON samples: poststress G_m (i.e., ΔG_m at zero injection time) increases for OX sample together with a much larger V_T shift than that of N2ON, but decreases for the N2ON sample. For the OX sample, this could be explained by a two-piece model:[23] the channel consists of an undamaged region and a damaged region near the drain end. The latter is formed by enhanced electron trapping and generation of oxide traps under heavier stress conditions and has a higher V_T but a much smaller length (<0.1 μm) as compared to the undamaged part of the channel.[24] Therefore, when the transductance ($\propto 1/L$) of the device under stress is gradually dominated by that of the growing damaged region, its value increases. For the N2ON sample, due to a harder gate oxide resulting from nitrogen

Downloaded 03 Nov 2006 to 147.8.21.97. Redistribution subject to AIP license or copyright, see http://jap.aip.org/jap/copyright.jsp

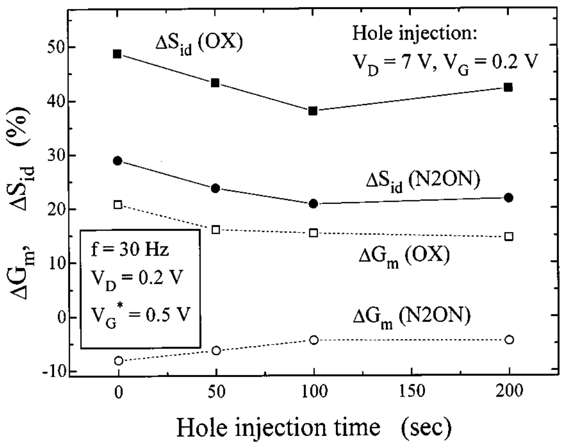

FIG. 6. Recoveries of ΔS_{id} and ΔG_m with hole injection after a 3000 s I_{Gmax} stress at $V_D = V_G = 8$ V.

incorporation, the corresponding damage is not so severe that G_m is still controlled by the total channel conductivity and thus decreases due to the resistance increase of the damaged region at the drain end. However, no matter how G_m's of the two sample change, their S_{id}'s exhibit a much larger degradation due to enhanced electron trapping and generation of oxide traps at the drain end under the heavier stress condition. Similarly, the degradations of the two samples are recovered to different extents by subsequent hole injection, as shown in Fig. 6, based on the same mechanism for the I_{Bmax} stress. The ratio of the recovered ΔS_{id} to total ΔS_{id} is ~22% for the OX sample and ~28% for the N2ON sample. For the OX sample, the smaller recovery than that in the I_{Bmax} stress is due to the fact that the latter has generations of not only interfacial oxide traps but also fast interface states while the former is mainly affected by the created interfacial oxide traps. The recovery of the N2ON sample is close to that in Fig. 2, further confirming the previous suggestion. Here, a turnaround phenomenon of ΔS_{id} similar to that in Fig. 2 also occurs for the same reasons after a 100 s hole injection. Therefore, it is plausible to consider the surface-mobility fluctuation as an origin of $1/f$ noise increase after hot-carrier stresses, which can lead to electron trapping at the fast interface states and interfacial oxide traps (e.g., I_{Bmax} and I_{Gmax} stresses).

IV. SUMMARY

Different stress conditions can degrade the $1/f$ noise of MOSFETs via different mechanisms: (1) for I_{Bmax} stress, carrier-number fluctuation plus surface-mobility fluctuation arising from electron trapping at fast interface states and interfacial oxide traps, including preexisting and newly generated ones; (2) for low-V_G stress, carrier-number fluctuation associated with hole trapping, and generation of neutral electron traps near the interface; and (3) for I_{Gmax} stress, carrier-number fluctuation resulting from created electron traps located at the gate oxide slightly farther from the interface and surface-mobility fluctuation caused by electron trapping at preexisting and newly generated interfacial oxide traps and preexisting fast interface states. As a result, maximum and minimum degradations of $1/f$ noise are observed for I_{Bmax} and I_{Gmax} stresses, respectively. However, through N_2O nitridation of the gate oxide, the $1/f$ noise degradation of devices under all these hot-carrier stresses can be significantly suppressed.

ACKNOWLEDGMENTS

This work is financially supported by the RGC and CRCG Research Grants, the University of Hong Kong.

[1] G. Ghibaudo, O. Roux-dit-Buisson, and J. Brini, Phys. Status Solidi A **132**, 501 (1992).
[2] M.-H. Tsai and T.-P. Ma, IEEE Trans. Electron Devices **ED-41**, 2061 (1990).
[3] C. Hu, J. Zhao, G. P. Li, E. Worley, J. White, and R. Kjar, IEEE Electron Device Lett. **EDL-16**, 61 (1995).
[4] J. A. Babcock, D. K. Schroder, and Y.-C. Tseng, IEEE Electron Device Lett. **EDL-19**, 40 (1998).
[5] Z. H. Fang, S. Christoloveanu, and A. Chovet, IEEE Electron Device Lett. **EDL-7**, 371 (1986).
[6] C. H. Cheng and C. Surya, Solid-State Electron. **36**, 475 (1993).
[7] P. K. Hurley, E. Sheehan, S. Moran, and A. Mathewson, Microelectron. Reliab. **36**, 1679 (1996).
[8] J. M. Pimbley and G. Gildenblat, IEEE Electron Device Lett. **EDL-5**, 345 (1984).
[9] M. Aoki and M. Kato, IEEE Electron Device Lett. **EDL-17**, 118 (1996).
[10] K. K. Hung, P. K. Ko, C. Hu, and Y. C. Cheng, in Tech. Dig. Int. Electron Devices Meet. 34 (1988).
[11] K. K. Hung, P. K. Ko, C. Hu, and Y. C. Cheng, IEEE Trans. Electron Devices **ED-37**, 1323 (1990).
[12] K. K. Hung, P. K. Ko, C. Hu, and Y. C. Cheng, IEEE Trans. Electron Devices **ED-37**, 654 (1990).
[13] L. Ren, S. Ohkonin, and M. Ilegems, Proceedings of International Conference on Noise in Physical Systems and 1/*f* fluctuations, 1997, Leuven, Belgium, 1997, p. 253.
[14] G. Hu and W. C. Johnson, Appl. Phys. Lett. **36**, 590 (1980).
[15] A. L. McWhorter, in *Semiconductor Surface Physics* (University of Pennsylvania Press, Philadelphia, 1957), p. 207.
[16] T. L. Meisenheimer, D. M. Fleetwood, M. R. Shaneyfelt, and L. C. Riewe, IEEE Trans. Nucl. Sci. **NS-38**, 1297 (1991).
[17] R. Jayaraman and C. Sodini, IEEE Trans. Electron Devices **ED-37**, 305 (1990).
[18] J. E. Chung, P. K. Ko, and C. Hu, IEEE Trans. Electron Devices, **ED-38**, 1362 (1991).
[19] B. S. Doyle, M. Bourcerie, C. Bergonzoni, R. Benecchi, A. Bravis, K. R. Mistry, and A. Boudou, IEEE Electron Device Lett. **EDL-37**, 1869 (1990).
[20] R. Bellens, P. Heremans, G. Groeseneken, and H. E. Maes, IEEE Electron Device Lett. **EDL-9**, 232 (1988).
[21] M. Brox and W. Weber, IEEE Trans. Electron Devices **ED-38**, 1852 (1991).
[22] B. Doyle, M. Bourcerie, J. -C. Marchetaux, and A. Boudou, IEEE Trans. Electron Devices **ED-37**, 744 (1990).
[23] C. Nguyen-Duc, S. Cristoloveanu, and G. Reimbold, IEEE Electron Device Lett. **EDL-9**, 479 (1988).
[24] N. S. Saks, D. M. McCarthy, and M. G. Ancona, *Proceedings of the Symposium on Low Temperature Electronics and High Temperature Superconductors*, Honolulu, HI, 19–23 Oct., 1987, p. 136.

Downloaded 03 Nov 2006 to 147.8.21.97. Redistribution subject to AIP license or copyright, see http://jap.aip.org/jap/copyright.jsp