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Analyses of the Carrier Mobilities of MISFETs with Silicate Gate Dielectrics

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Comprehensive analyses of the carrier mobilities in MISFETs with thin HfSiON gate dielectrics have been performed. Through careful examination of the temperature dependence of the mobilities in nMIS and pMIS structures, the main scattering mechanisms of the electrons and holes for various effective field (Eeff) regions associated with the high-k gate stack were determined. Remote Coulomb scattering dominates the mobility in the low Eeff region both for electrons and holes. It has also been revealed that the remote phonon scattering is the major scattering mechanism for nMIS in the medium Eeff region, whereas it is not for pMIS. Although surface roughness scattering dominates the scattering mechanism in the high Eeff region, the presence of Hf and N in the gate dielectric modifies the scattering in different manners for electrons and holes.

Key words:mobility, high-k, silicate, MISFET

1. INTRODUCTION

Down-scaling of MIS transistors to the sub-50nm technology node is prompting many technological challenges concerning various parts of the nano-structure, including the demand for the realization of an ultra-thin (less than 2nm) gate dielectric stack. A large intrinsic leakage current is expected for such a thin film with conventional gate dielectric materials such as SiO2 or SiON, leading to a substantial power consumption increase of ULSIs. Therefore, investigations on high-k gate stacks are being conducted intensively. Several characteristics are required for the alternative gate insulator: The realization of low leakage current through the film requires a large dielectric constant and a large barrier height for electrons and holes that try to penetrate the bandgap. Reliability against TDDB, BTI and hot carriers is also of great concern. Good thermal stability above 1000°C must be satisfied for the application to the conventional LSI fabrication processes. Furthermore, smaller scattering probability of electrons and holes is indispensable in order to maintain high drive current of MISFETs with high-k gate dielectrics.

HfSiON is regarded as one of the most promising candidates for gate dielectric materials. It has been reported that this material shows high dielectric constants [1] and relatively large bandgaps [2]. These attributes resulted in a large leakage current suppression relative to conventional SiO_2 [1]. Good reliability of this material has also been reported recently [3]. Moreover, the high thermal stability of HfSiON against the phase separation and the impurity diffusion through the thin film makes it one of the most promising materials [1,4].

Recently, MISFETs using this material with carrier mobilities comparable to those of SiO_2, especially in the high effective field range, have been reported [3,5-8] from many institutes, however, the scattering mechanisms determining or influencing electron and hole mobilities are unclear for the entire range of the effective electric field, Eeff. Through careful examination of the temperature dependence of the mobilities in nMIS and pMIS structures, we extracted the scattering mechanisms of the electrons and holes associated with the high-k gate stack for various Eeff regions. We also revealed the influence of Hf and N presence in the gate dielectric.

2. EXPERIMENTAL

NMIS and pMIS transistors with HfSiON gate dielectrics and poly-Si gate electrodes were fabricated by the conventional CMIS processes. The channel impurity level was kept low (about $3\times10^{16}cm^{-3}$) in order to avoid the large substrate impurity scattering in this experiment. Thin films of Hf silicate with Hf relative concentration (Hf/Hf+Si) of 50% were deposited using metal organic chemical vapor deposition (MOCVD) on hydrogen-terminated Si surface. The equivalent oxide thickness (EOT) of these films was around 2.0nm. Post-deposition annealing (PDA) was carried out in O_2 ambient. Nitridation using Ar/N mixed plasma at RT was performed, followed by post-nitridation annealing (PNA). High-temperature rapid thermal annealing for the impurity activation was carried out above 1000°C. MOSFETs with the conventional SiO_2 gate dielectrics were also fabricated using the same process as reference samples.

3. RESULTS AND DISCUSSION

3.1 Characterization of HfSiON gate stack

Figure 1 shows the interface states of the HfSiON gate stack measured with the charge pumping technique. The frequency dependence of the charge pumping current indicates that the interface trap density of HfSiON is about $5\times10^{10}cm^{-2}eV^{-1}$ (Fig. 1), which is a little larger than that of SiO2 but still very small. The interface states did not show large thickness dependence. We concluded that the influence of these traps on the mobility is negligible [9].

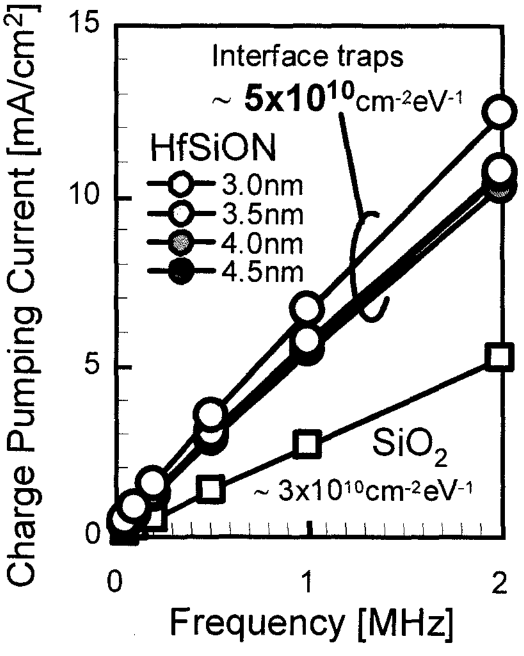

Fig. 1. Charge pumping currents as a function of frequency in the MISFETs with the HfSiON gate insulator of various thicknesses. The result for the conventional MOSFET with SiO2 gate insulator is also shown.

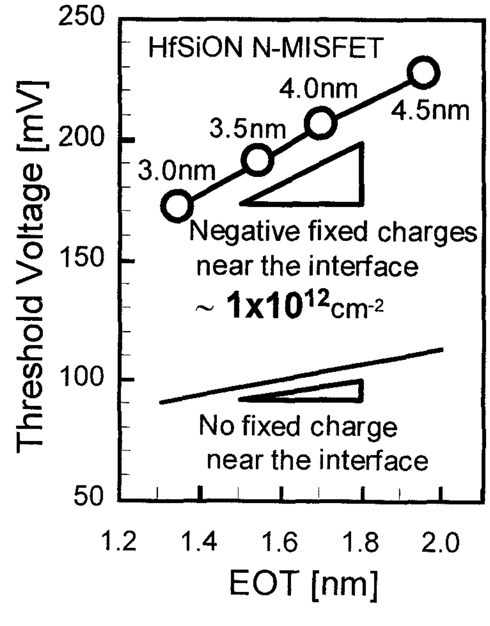

Fig. 2. Dependence of the threshold voltage Vth of nMISFET on the EOT of the high-k stack. The Vth dependence of EOT expected for the MISFET without any fixed charge is also shown as a reference. The Vrh increase rate as a function of EOT for HfSiON MISFETs is larger than the ideal case.

Figure 2 shows the dependence of nMIS threshold voltage Vth on the EOT of the high-k stack. Vth increased with the EOT increase almost linearly. The Vth expected for the nMISFET without fixed charges is also shown. Although the EOT increase itself leads to larger threshold voltage, the slope of Vth increase of MISFET with HfSiON surpassed that of the ideal one. Therefore, it is expected that a negative fixed charge is located near the interface and the amount was estimated to be as large as $1\mathrm{x}10^{12}\mathrm{cm}^{-2}$, which enhances the scattering probability of the carriers in the channel as shown below. Similar analyses have been performed for pMISFETs and they indicated the same results.

3.2 Mobility analyses of nMISFET

Figure 3 shows the electron mobility as a function of the effective electric field Eeff in the nMISFET with HfSiON gate dielectric. Measurement temperature is taken as a parameter in this figure. The mobility in MOSFET with the conventional SiO2 gate insulator is also shown. The electron mobilities decreased with the increase in the measurement temperature for both cases, however, they are lower with HfSiON than those for MOSFET with SiO2 for the entire effective field region at any temperature measured. These results also indicate that the mobility is particularly low at the low Eeff region. In order to extract the scattering components inherent to HfSiON, the following equation was used, assuming the validity of Matthiessen's rule:

$$\Delta\mu \equiv \left(\frac{1}{\mu_{HfSiON}} - \frac{1}{\mu_{SiO2}}\right)^{-1} \qquad (1)$$

where μ_{HfSiON}, μ_{SiO2} and $\Delta\mu$ are mobilities measured for the HfSiON MISFET, for the SiO2 reference MOSFET and the additional mobility component associated with HfSiON, respectively.

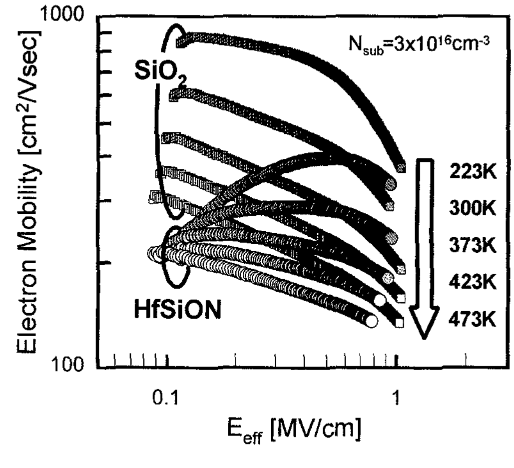

Fig. 3. Electron mobility as a function of the effective electric field in the nMISFET with HfSiON gate dielectric. Measurement temperature is taken as a parameter in this figure. Also shown is the mobility in MOSFET with the conventional SiO2 gate insulator.

Figure 4 shows the Δμ dependence on the inversion carrier density Ns, taking measurement temperature as a parameter. It is found that Δμ at low temperature, for example 223K, significantly increases with an increase in Ns. This fact indicates that the mobility degradation at low temperature is mainly due to Coulomb scattering associated with charges in dielectrics [10], since the strong screening effects make the probability of Coulomb scattering small in the high N_s region [12]. However, this figure also shows a phenomenon which cannot be explained only with the Coulomb scattering model: the Ns dependence of Δμ is weaker for higher measurement temperatures. Since similar screening effects are expected even at higher temperatures for Coulomb scattering, this phenomenon is inconsistent with this model.

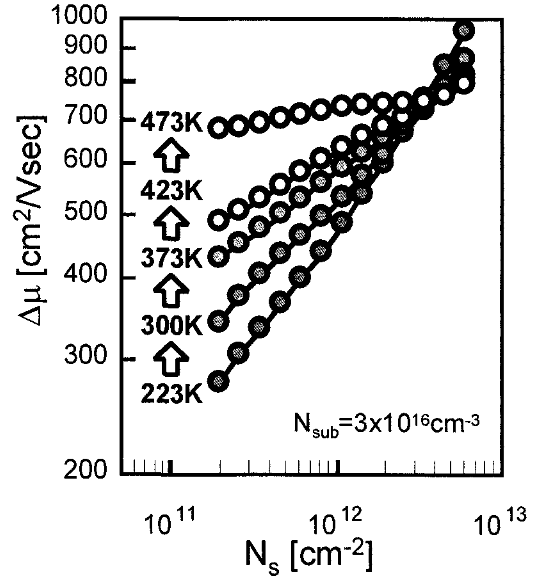

Fig. 4. Δμ dependence on the inversion carrier density Ns. The measurement temperature was varied from 223K to 473K.

In fact, mobility slightly decreases with an increase in temperature at the high Ns region. If the mobility degradation is due only to the Coulomb scattering, Δμ should at least increase for higher temperatures irrespective of Ns, since the high average kinetic energy of inversion-layer electrons makes the probability of Coulomb scattering small at high temperature [11,12]. Therefore, it is reasonable to suppose that another scattering mechanism exists in higher Ns, namely higher Eeff region.

Figure 5 shows the additional mobility curves in low and medium Eeff regions at various measurement temperatures. It is clearly observed that the mobility in the medium Eeff region decreases with the increase in the measurement temperature, in spite of the increase in low Eeff range. We believe that this is explained in terms of the remote phonon scattering [13,14] associated with the soft phonon in HfSiON.

Figure 6 shows the electron mobility as a function of the effective electric field in the nMISFET with HfSiON gate dielectric at temperatures including very low regions (22K-123K). Mobility in MOSFET with the conventional SiO2 gate insulator is also shown. It is observed that the mobility at low measurement temperatures converges on one line both for HfSiON and SiO2 cases. Since it is considered that the amount of phonons causing scattering dramatically decreases at low temperatures and that the surface roughness scattering does not depend largely on temperature [15], this convergence line is thought to be determined by the roughness scattering. Compared with the scattering on the Eeff for MOSFET with SiO2, that of HfSiON has weaker dependence on the Eeff as shown by the long dash lines in Fig. 6.

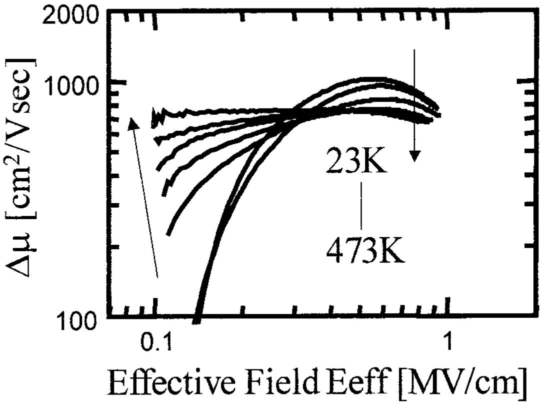

Fig. 5. Additional mobility curves in low and medium Eeff regions at various measurement temperatures (23K-77K-223K-300K-373K-423K-473K).

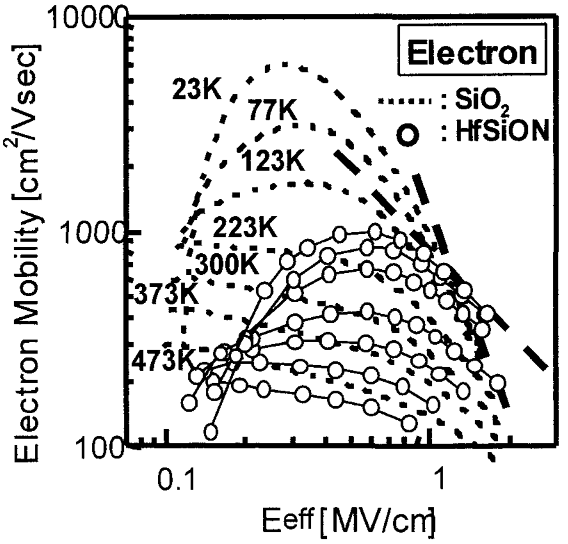

Fig. 6. Electron mobility as a function of the effective electric field in the nMISFET with HfSiON gate dielectric at temperatures including very low regions (22K-123K). Mobility in MOSFET with the conventional SiO2 gate insulator is also shown. Long dash lines indicate the dependence of the electron mobility on Eeff.

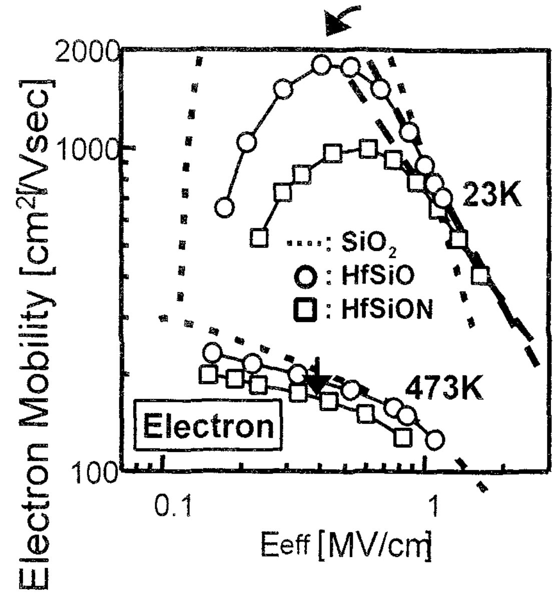

Fig. 7. Electron mobility as a function of Eeff for nMISFET with HfSiO and HfSiON. The results for two measurement temperatures are shown.

In order to distinguish the influence of Hf and N in gate dielectrics, a MISFET with HfSiO was also fabricated and compared with the result for HfSiON. Figure 7 shows the electron mobility as a function of Eeff of this device. The results are shown for two measurement temperatures, 23K and 473K. The long dash lines represent the electron mobility dependence on Eeff at the high Eeff region. That of HfSiO shows that the weak dependence is observed even only with Hf present in the gate dielectric. With further N incorporation, however, a much weaker tendency is observed for the Eeff where the surface roughness scattering dominates.

Although the above-mentioned phenomenon has not been explained yet, a few possible explanations exist, such as a change in the roughness mean square (RMS) or the correlation length. Even a modification of the roughness correlation function itself may lead to a change of the dependency and the absolute value of the mobility. This figure also reveals that in addition to the decrease in the electron mobility due to the Hf present in the gate dielectric, the N incorporation further decreases the electron mobility in the medium Eeff range where the remote phonon scattering dominates. A study of the change in the phonon energy due to the N incorporation should be performed in order to elucidate the reason for this phenomenon.

3.3 Mobility analyses of pMISFETs

Figures 8 shows the hole mobility dependence on the Eeff in pMISFETs with (a) SiO2 and (b) HfSiON gate dielectrics. The measurement temperature was varied from 23K to 473K. As in the case of the electron mobility, the hole mobilities of the HfSiON MISFET generally showed lower values than those of the conventional SiO2 MISFET. By using equation (1), the mobility component associated with HfSiON thin film was extracted as $\Delta\mu$. The roughness scattering component in HfSiON MISFETs is not necessarily the same as that in SiO2 MISFET. Therefore, the roughness scattering component of SiO2 MISFET was modeled and removed from μ_{SiO2}, prior to $\Delta\mu$ calculation by equation (1). This procedure directly provided the roughness scattering component in the HfSiON MISFET as shown below.

Figure 9 shows $\Delta\mu$ as a function of Eeff. The measurement temperature is taken as a parameter. The mobility in the low Eeff region decreased due to the decrease in the measurement temperature with a large Eeff dependence. This is characteristic of the Coulomb scattering as also shown in Figs. 4 and 5 for the electron mobility.

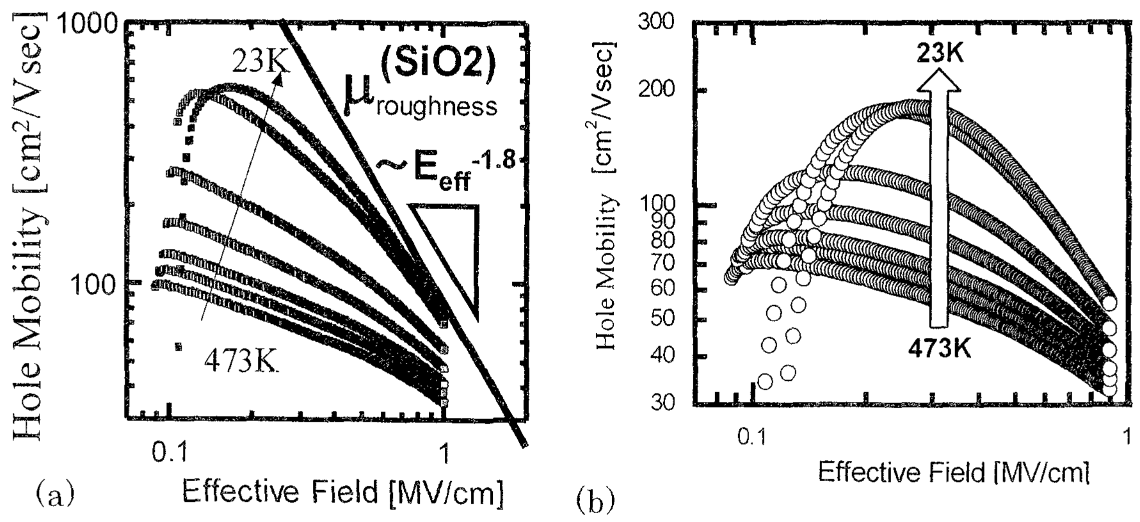

Fig. 8. Hole mobility dependence on the effective field in pMISFETs with (a) SiO2 and (b) HfSiON gate dielectrics. The measurement temperature was varied from 23K to 473K.

Since the same amount of fixed charge exists in the high-k stack in pMISFETs as mentioned above, it is reasonable that this component is also observed in these devices.

The difference between hole and electron mobilities emerges especially in the medium Eeff region: Although the mobility component, which decreases as the measurement temperature increases, is observed for the electron mobility as in Fig. 5, it is not present in the case of the hole mobility. On the other hand, another scattering component which does not have large temperature dependence dominates medium and high Eeff regions. This component is considered to originate in the roughness scattering in the HfSiON gate stack. Comparison of this component with that in the SiO2 gate stack indicates Eeff dependence similar to that of the reference device, but lower mobility value. This phenomenon for the hole mobility also differs from that in the case of the electron mobility.

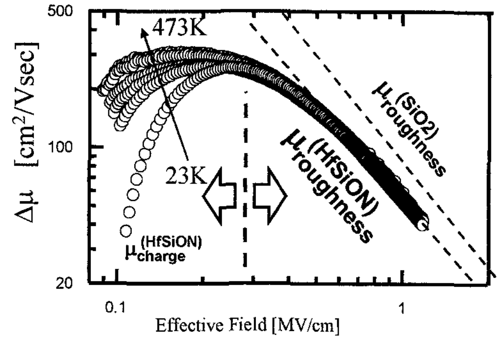

Fig. 9. Δμ as a function of Eeff. The measurement temperature is taken as a parameter.

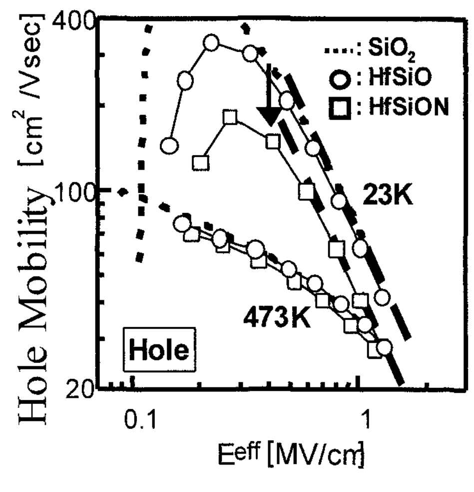

Fig. 10. Electron mobility as a function of Eeff for HfSiO and HfSiON pMISFETs. The measurement temperature is taken as a parameter.

In order to distinguish the influence of Hf and N in gate dielectrics, pMISFET with HfSiO was also fabricated and compared with the result for HfSiON. Figure 10 shows the hole mobility as a function of Eeff. The results are shown for two measurement temperatures, i.e. 23K and 473K. The long dash lines represent the dependence of the hole mobility on Eeff at the high Eeff region. That of HfSiO shows almost the same value as in the SiO2 pMISFET. With further N incorporation, however, the mobility was suppressed although its Eeff dependence remained the same. Further investigation is needed to arrive at a satiscactory explanation of this phenomenon. No clear remote phonon component was observed for either HfSiO or HfSiON pMISFET, even at 473K.

3.4 Further improvement of the carrier mobility in HfSiON MISFETs

As mentioned above, the electron and hole mobilities in HfSiON MISFETs generally show lower values than those in SiO2 MISFET, except in the case of very high Eeff region in nMISFETs. Since mobility in the high Eeff region directly influences the driveability of transistors, it should be enhanced as much as possible. Electron mobility is suppressed by the remote phonon scattering as well as the surface roughness scattering in these Eeff regions, whereas the hole mobility is suppressed mainly by the surface roughness scattering. Since it has been revealed that N incorporation enhances the scattering probability of these components, an intensive investigation on the influence of the amount and location of Hf and N should be conducted. In fact, nitrogen depletion from the interface between the gate insulator and the substrate has been reported to be effective in enhancing the mobility in the high Eeff region for SiON [16]. Considering that the N incorporation is indispensable to keep the thermal stability of the high-k material [1,4], the amount and/or the location of this element should be optimized through close investigation. Since electron and hole mobilities are determined by the Coulomb scattering, which originates in charges in HfSiON films in the low Eeff region, measures for reducing the amount, such as the optimization of the formation processes are necessary in the case that the scattering component influences the mobility in the high Eeff region [17].

4. CONCLUSIONS

Comprehensive analyses on the carrier mobilities in MISFETs with thin HfSiON gate dielectrics have been conducted. Through careful examination of the temperature dependence of the mobilities in nMIS and pMIS structures, the main scattering mechanisms of the electrons and holes for various Eeff were determined. Remote Coulomb scattering dominates the mobility in the low Eeff region both for electrons and holes. It has also been revealed that the remote phonon scattering is the main scattering mechanism for nMIS in the medium Eeff region, whereas it is not for pMIS. Although surface roughness scattering governs in the high Eeff region, the presence of Hf and N in the gate dielectric modifies the scattering in different manners for electrons and holes.

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