Noncontact probing of metal-oxide-semiconductor inversion layer mobility

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We have measured absorption of terahertz radiation pulses by metal-oxide-semiconductor (MOS) inversion layers and thereby determined carrier mobility without the need for source and drain contacts. This has allowed for the determination of inversion layer mobility prior to subsequent high temperature processing. An unannealed MOS sample was found to have a mobility value of 400 $\mathrm{cm}^2/\mathrm{V\,s}$, which increased to 700 $\mathrm{cm}^2/\mathrm{V\,s}$ after a 950 °C anneal. © *1996 American Institute of Physics.* [S0003-6951(96)04338-0]

Inversion layer mobility is one of the most important device parameters in metal-oxide-semiconductor (MOS) technology. The mobility is usually obtained by measuring the drain current versus the drain voltage for a given gate voltage or versus the gate voltage for a given drain voltage.[1] However, this requires a full transistor structure including gate, source, and drain.

A noncontact characterization of carrier mobility in semiconductors may be done by using terahertz (THz) electromagnetic pulses generated by photoconductive antenna technology.[2] In a similar manner, mobility in MOS inversion layers can be characterized if the attenuation due to a inversion layer can be measured. One of the unique applications of this technique is for studying the annealing temperature dependence of inversion layer mobility, because this method needs a simple MOS capacitor instead of a full processed transistor. The mobility at different annealing conditions is difficult to characterize, due to the necessity of high-temperature processing in the formation of source and drain contacts, although the behaviors of oxide charges and interface traps have been well investigated at different annealing temperatures and ambients.[5–7] Utilizing the THz pulse technique we have been able to study the annealing temperature dependence of MOS inversion layer mobility without altering other experimental conditions.

To fabricate MOS samples, 1500-Å-thick thermal oxide was grown for 300 min at 1000 °C on B-doped 18-Ω cm Si wafers and followed by 200-Å LPCVD poly-Si gate doped *in situ* with P. The gate was patterned using conventional techniques. The gate size is 2×2 cm to accommodate the full size of the THz beam. Several MOS capacitors were fabricated simultaneously and subsequently annealed at different temperatures after gate patterning. One sample was not annealed, and two were annealed at 800 and 950 °C, respectively, for 30 min in N_2. With these three samples quasistatic capacitance–voltage (C–V) measurements were performed. For the unannealed sample the flat-band voltage (V_{FB}) occurs at -2.1 V due to the high densities of positive oxide charges and interface traps[6,12] while that of the 800 and 950 °C annealed samples occur at -2.0 and -1.6, respectively. MOS capacitors annealed at higher temperatures show smaller negative values of V_{FB} which indicate the number of oxide charges and interface traps decreases.

The THz transmitter and receiver were fabricated on low-temperature-grown (LT) GaAs with a subpicosecond carrier lifetime.[8,9] Al coplanar strip lines are lithographically fabricated on the LT-GaAs to serve as an antenna and bias line. The separation between the two lines is 25 μm with taps spaced by 5 μm in the middle of the lines. The antennas on LT-GaAs are mounted on high-resistivity hyperhemisphere Si lenses to collimate the THz pulse beam. The THz pulses are driven using a self-mode-locked Ti:sapphire laser with 100-fs FWHM, 800-nm pulses at a repetition rate of 100 MHz.[10,11] The laser beam is focused on the 5-μm gap between the strip line taps on the transmitter, generating THz electromagnetic pulse. This radiated pulse is detected by a subpicosecond photoconductive gate driven by a part of the laser beam. The sampled signal is fed to a current preamplifier and lock-in amplifier.

To probe the inversion layer mobility, the MOS capacitor is inserted between the transmitter and receiver as shown in Fig. 1, with a positive gate bias to form an inversion layer. With a bias of 45 V to the gate of the unannealed sample, the THz pulse transmission drops by 3% in amplitude compared to the unbiased case. As shown in Fig. 2, the waveforms are almost identical and the transmission spectrum due to inversion layer is fairly flat up to 2 THz which is verified by taking the Fourier transform of each curve and calculating the ratio. The amount of transmission decrease is linearly proportional to the inversion charge density and mobility when the transmission change is small. The inversion charge density is determined from the C–V data and increases lin-

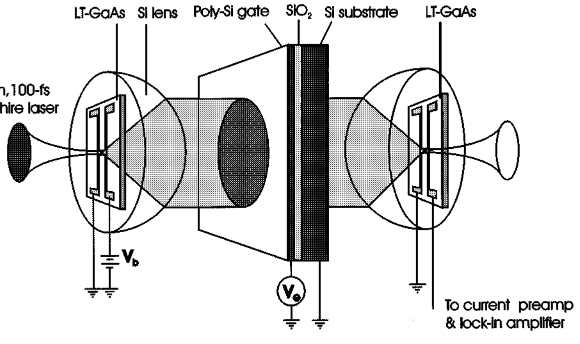

FIG. 1. Schematic diagram of the experimental setup. A biased metal-oxide-semiconductor (MOS) capacitor is inserted between the photoconductively driven transmitter (left-hand side) and receiver.

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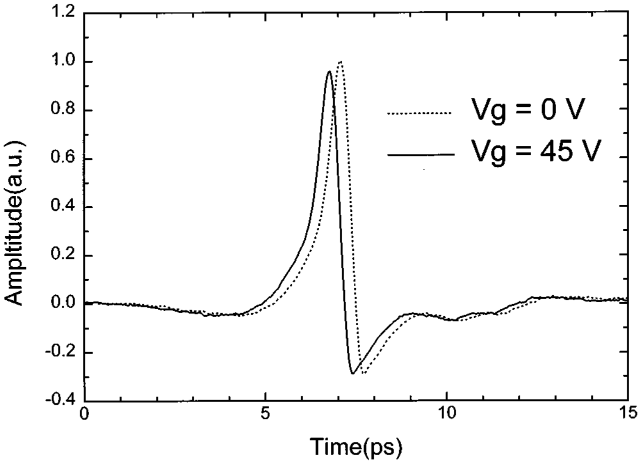

FIG. 2. Time-domain terahertz (THz) pulses transmitting through a MOS capacitor at two different gate voltages. One waveform is displaced intentionally for clarity.

early with the gate voltage above 2 V. An inversion charge density of 6×10^{12} cm^{-2} is obtained at a gate voltage of 45 V. At different gate voltages we measure wave forms similar to those shown in Fig. 2. The transmission is defined as a peak-to-peak amplitude and plotted in Fig. 3 for the unannealed and 950 °C annealed samples. As can be seen in the figure, the transmission change of the annealed sample is 3.5% at a voltage of 30 V while that of the unannealed sample is only 2%. This indicates that the mobility of the annealed sample is nearly two times larger than that of the unannealed sample.

To determine the mobility from the measurements we calculated the THz pulse transmission through the thin layer system of poly-Si, SiO_2, and inversion layer on top of the Si substrate. The complex dielectric constant of the poly-Si gate is obtained from a literature value of the refractive index (3.7) and from the resistivity (0.0035 and 0.013 Ω cm for the annealed and unannealed, respectively) drawn from the comparison of THz pulse transmissions through the regions with and without the poly-Si gate. Although the effect of gate resistivity difference is minimal, the variation is taken to account in the mobility extraction. The dielectric constant of gate oxide is 3.9. The complex dielectric constant of the inversion layer is calculated using the Drude model. This model includes the scattering rate of inversion electrons which is inversely proportional to the mobility.[3,4] We adjust this scattering rate to fit the calculation to the measurement result. The inversion charge density per unit area is obtained from the measured C–V data. In the calculation we calculated the cw monochromatic wave at a frequency of 500 GHz. This is valid because the measured frequency spectrum of the transmission through the inversion layer is almost flat up to 2 THz. Interference occurring at interfaces between gate, insulator, and the inversion layer was taken into account while it was ignored at the substrate and air interface because the substrate is thick enough for a THz pulse and its reflections to be separated in time domain. Repeating the calculation at other frequency gives a similar result. From the fit to the transmission measurement, the average mobilities for the unannealed and annealed samples are 400 and 700 $\mathrm{cm}^2/\mathrm{V\,s}$, respectively.

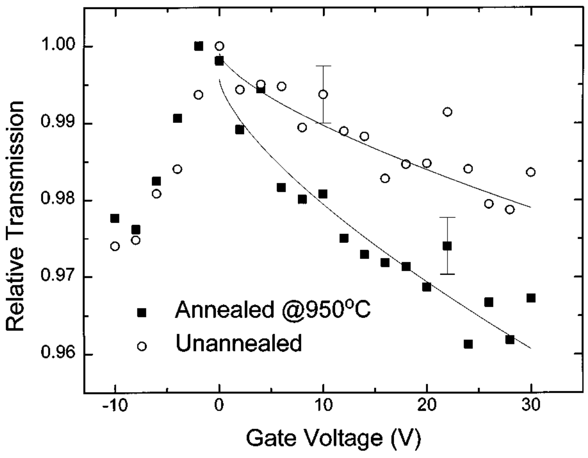

FIG. 3. Normalized amplitude of THz pulse transmission through unannealed and annealed MOS samples with respect to the gate voltage. The solid lines are a guide to the eye. Error bar shown above applies to all points on the same graph.

While this method can clearly detect the MOS inversion layer mobility, improvement of the signal-to-noise ratio can be made by averaging out the laser noise by using a fast scan to acquire the wave form faster or by using a bolometer to detect the total transmitted energy. The demonstration of MOS mobility measurement with improved sensitivity using freely propagating electromagnetic pulses will open many potential applications including rapid in-line process control and monitoring of the effect of subsequent high-temperature process steps on mobility. This technique offers a unique method to study the mobility characteristics due to the epitaxial structure at the SiO_2/Si interface which is known to diminish substantially with thermal annealing.[13]

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