A signal processing method for the friction-based endpoint detection system of a CMP process*

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Abstract: A signal processing method for the friction-based endpoint detection system of a chemical mechanical polishing (CMP) process is presented. The signal process method uses the wavelet threshold denoising method to reduce the noise contained in the measured original signal, extracts the Kalman filter innovation from the denoised signal as the feature signal, and judges the CMP endpoint based on the feature of the Kalman filter innovation sequence during the CMP process. Applying the signal processing method, the endpoint detection experiments of the Cu CMP process were carried out. The results show that the signal processing method can judge the endpoint of the Cu CMP process.

Key words: CMP; endpoint detection; signal processing
DOI: 10.1088/1674-4926/31/12/126002 **EEACC:** 7220

1. Introduction

With the development of integrated circuits (ICs) toward high speed and high integration, the interconnection line density is increasing and the line width is continuously narrowing. To resolve the reliability problems caused by the RC delay and electromigration of the metal interconnection lines, Cu has already replaced Al as the interconnection metal beyond the 0.18 μm technology node. The Damascene process is extensively used to form the multilayer Cu interconnection structures. The Damascene process mainly involves depositing dielectric material; forming a pattern by lithography and etching; depositing a barrier layer, a seed crystal layer and Cu; removing the excessive materials using a planarization process, etc. After multiple repetitions of the above processes, a multilayer Cu interconnection structure is formed[1]. As shown in Fig. 1, after depositing Cu, the surface is not flat; to meet the requirements of the lithographic process, it is necessary to remove the excessive materials using a planarization process. Chemical mechanical polishing (CMP) has been extensively used in the ULSI manufacturing process as the most effective global planarization technology; however, during the Cu CMP process, over-polishing (removing too much) and under-polishing (removing too little) often occur. Over-polishing results in excessive copper dishing and dielectric erosion, causing the degradation of device performance or yield; under-polishing needs to be reworked, leading to an increase in IC fabrication cost. Therefore, fast, accurate and reliable CMP endpoint detection (namely to determine when to stop CMP) is a key piece of technology to assure the quality of CMP processing and improve the yield and efficiency[2].

Many CMP endpoint detection methods have been proposed, such as optical, frictional, acoustic, and electrical methods. The representative methods for CMP endpoint detection are the optical and frictional methods. However, for the Cu CMP process, the effects of the scattering and diffraction caused by the existence of copper interconnection lines make it difficult to judge the CMP endpoint[2,3]. The frictional methods judge the CMP endpoint by detecting the change in the friction coefficient, torque or motor current during the CMP process. Compared with the optical methods, the frictional methods are relatively more economical to implement[4]. However, for the frictional endpoint detection methods, because the acquired signal contains much noise and the change of signal is weak, to judge the CMP endpoint accurately, an effective signal processing method is necessary. The signal processing method based on the feature in some frequency range has been studied[5,6]. However, there are few studies on the signal processing method based on the time domain feature.

In this paper, a signal processing method for a friction-based CMP endpoint detection system was presented; applying the signal processing method, the endpoint detection experiments of the Cu CMP process were carried out.

2. Signal processing method

2.1. Wavelet denoising

To judge accurately the endpoint during the Cu CMP process, an effective denoising method is necessary because the original signal contains much noise. The wavelet denoising method is a nonlinear denoising method based on the wavelet decomposition. Compared with the traditional low pass filters, the wavelet denoising method can not only realize the function of low pass filter but also maintain the feature of the signal. Among the different methods of wavelet denoising, the wavelet threshold denoising method is applied widely and can meet the needs of real time[7]. Therefore, in this paper, the wavelet threshold denoising method is used to reduce the noise con-

* Project supported by the Major Program of National Natural Science Foundation of China (No. 50390061) and the National Science and Technology Major Project, China (No. 2009ZX02011).
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Received 9 August 2010, revised manuscript received 30 September 2010

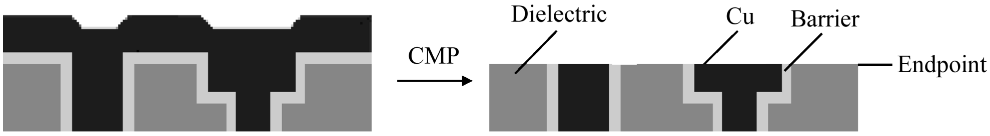

Fig. 1. Schematic diagram of the Cu CMP process.

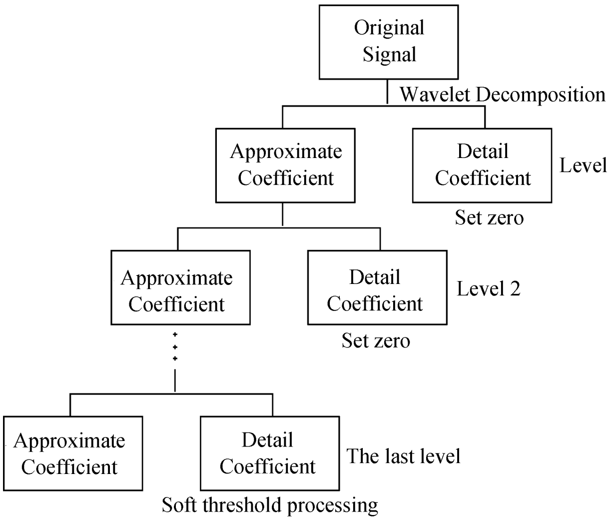

Fig. 2. Processing method of the wavelet coefficients.

tained in the original measured signal.

The key to the wavelet threshold denoising method is the determination of the threshold and the selection of the threshold function. Because during the Cu CMP process the change in the friction coefficient is slow, the high frequency part of the measured signal is mainly noise. Based on the feature of the friction coefficient signal, the last level of the detail coefficients is processed by the general threshold processing method and the other levels of the detail coefficients are set to be zero; the soft threshold function is selected. Figure 2 shows the wavelet coefficient processing method.

For the offline wavelet denoising, all of the measured data are processed as a set. For the CMP endpoint detection process, to meet the needs of real time, a moving block strategy is presented. As shown in Fig. 3, the measured data are grouped into the overlapping blocks of chosen length. The wavelet denoising begins as soon as the first block of data is collected. The processes of grouping the measured data into the blocks and wavelet denoising are repeated until the CMP process ends. This method results in a short time delay; however, it can reduce the edge effect and this time delay can be made trivial by the high computational speed and the high rate of data sampling.

2.2. Feature extraction

The feature extraction of the signal is a key step in the process of CMP endpoint detection. The feature must contain the necessary discriminative information for the Cu CMP process. In this paper, the Kalman filter innovation sequence is considered as the feature signal to judge the endpoint during the Cu CMP process.

The Kalman filter is a set of mathematical equations that provide an efficient computational means to estimate the state of a process in a way that minimizes the mean of the squared error. During the Cu CMP process, the signal will accordingly change when the polished materials change (transiting from whole Cu to Cu and Ta), and the signal will maintain correspondingly steady when the polished materials are stable (whole Cu or reaching CMP endpoint). Based on the feature of the signal during the Cu CMP process, the signal model and the measurement model are built as follows,

$$x_k = x_{k-1} + w_{k-1}, \quad (1)$$

$$y_k = x_k + v_k, \quad (2)$$

where x is a sequence of the state signal and y is a sequence of the measured value; the random variable w and v are respectively the process noise and measurement noise. They are assumed to be independent, zero-mean Gauss white noise.

The Kalman filter equations are as follows,

$$\hat{x}_k = \hat{x}_{k-1} + b_k[y_k - \hat{x}_{k-1}], \quad (3)$$

$$b_k = p_k^-[p_k^- + \sigma_v^2]^{-1}, \quad (4)$$

$$p_k^- = p_{k-1} + \sigma_w^2, \quad (5)$$

$$p_k = [1 - b_k]p_k^-, \quad (6)$$

where Equations (3) and (4) are respectively the filter equation and the gain equation; $\hat{x}_k$ and $\hat{x}_{k-1}$ are the state estimate of the sample k and k-1; P_k^- and P_k are, respectively, the priori estimate error covariance and the posteriori estimate error covariance; and b_k is the Kalman gain.

The Kalman filter innovation e_k is as follows,

$$e_k = y_k - \hat{x}_{k-1}. \quad (7)$$

The innovation sequence has the same feature as the original signal, and the innovation sequence will be a zero-mean Gauss white noise sequence when the signal model can well describe the feature of the measured signal[8]. Based on the feature of the Kalman filter innovation, when the innovation sequence is a zero-mean Gauss white noise sequence, it is indicated that the signal model can well describe the feature of the measured signal, namely the polished materials are stable; in contrast, when the innovation sequence is not a zero-mean Gauss white noise sequence, it is indicated that the signal model can not exactly describe the feature of the measured signal, namely the polished materials are changing. Therefore, based on the feature of the Kalman filter innovation, the endpoint during the Cu CMP process can be judged.

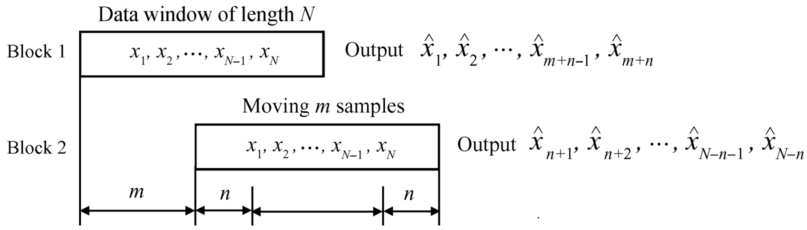

Fig. 3. Moving block strategy.

3. Judgment of the CMP endpoint

To determine accurately the CMP endpoint and realize the automation of the Cu CMP process, a CMP endpoint judgment criterion based on the standard deviation of the Kalman filter innovation sequence is presented.

To make the sequence of Kalman filter innovation smooth enough, the innovation sequence is processed using a sliding average value filtering method, and the filtered sequence is E_i. Based on Chebyshev's inequality, when the innovation sequence is a zero-mean Gauss white noise sequence, for any positive real number ε, the following inequality always exists,

$$P(|E_i| \geqslant \varepsilon) \leqslant \frac{\sigma^2}{\varepsilon^2}, \tag{8}$$

where σ^2 is the variance of the sequence E_i.

Assuming that the threshold coefficient n is positive real number and $\varepsilon = n\sigma$, the inequality (8) can be transformed as

$$P(|E_i| \geqslant n\sigma) \leqslant \frac{1}{n^2}. \tag{9}$$

Based on the feature of innovation mentioned in Section 2.2, when the polished materials maintain stable (whole Cu or reaching the CMP endpoint), the innovation will be in the following threshold range C,

$$C = [-n\sigma, n\sigma]. \tag{10}$$

During the practical CMP endpoint detection process, the standard deviation σ is replaced by the sample standard deviation evaluation S; the threshold coefficient is set to be 3, because the innovation sequence is usually a normal distribution. Then the threshold range can be written as

$$C = [-3S, 3S]. \tag{11}$$

The standard deviation of the innovation sequence S can be calculated as

$$S = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(E_i - \overline{E})^2}, \tag{12}$$

where $\overline{E}$ is the average value of the filtered innovation sequence and N is the number of samples.

The average value $\overline{E}$ can be calculated as

$$\overline{E} = \frac{1}{N}\sum_{i=1}^{N} E_i. \tag{13}$$

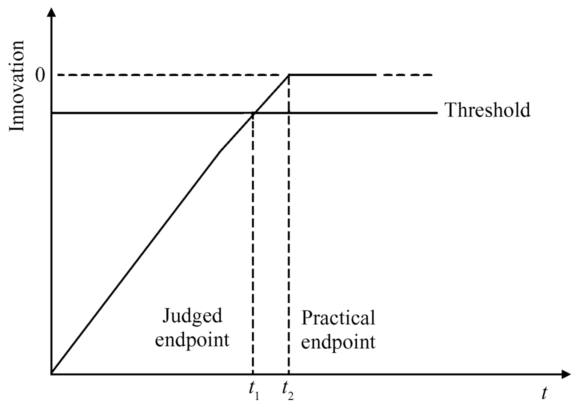

Fig. 4. Schematic diagram of time error.

To reduce the calculation time, $\overline{E}$ and S can be calculated using the iterative method. The formulas are as follows,

$$\overline{E}_N = \overline{E}_{N-1} + \frac{1}{N}[E_N - \overline{E}_{N-1}], \tag{14}$$

$$S_N = \sqrt{\frac{N-2}{N-1}S_{N-1}^2 + \frac{1}{N}[E_N - \overline{E}_{N-1}]^2}, \tag{15}$$

where E_N is the sample N of the filtered innovation sequence; $\overline{E}_N$ and $\overline{E}_{N-1}$ are, respectively, the average value of the current N samples and the previous $N-1$ samples, not including the sample N; and S_N and S_{N-1} are, respectively, the standard deviation of the current N samples and the previous $N-1$ samples, not including the sample N.

For the Cu CMP process, the innovation is negative when the polished material transits from whole Cu to Cu and Ta, so the interval threshold can be changed to the following single threshold T,

$$T = -3S. \tag{16}$$

Equation (16) can be used to judge whether the CMP endpoint has been reached or not. However, it is not accurate enough if Equation (16) is directly used to judge the CMP endpoint; the error that might occur is as shown in Fig. 4. The time ΔT can be approximately calculated as

$$\Delta T = t_2 - t_1 = \left|\frac{T}{d}\right|, \tag{17}$$

where d is the average value of the deviation of filtered innovation sequence E_i, and it can be calculated as

$$d = \frac{1}{N}\sum_{i=1}^{N}\frac{E_i - E_{i-1}}{\Delta t}, \tag{18}$$

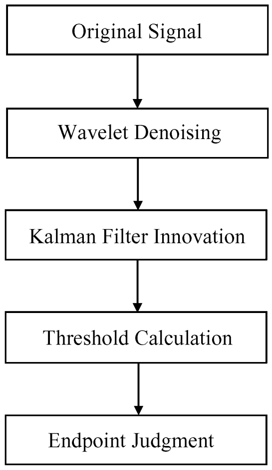

Fig. 5. Process of judging the CMP endpoint.

where Δt is the sampling period; N is the number of the samples.

The process of signal processing is shown in Fig. 5. First, the noise contained in the original signal is reduced by the wavelet threshold denoising method; then the feature signal, Kalman filter innovation sequence, is extracted from the denoised signal; finally, the CMP endpoint is judged based on the feature of the Kalman filter innovation.

4. Results and discussion

Applying the signal processing method, the endpoint detection experiments during the Cu CMP process were carried out. The signals of friction coefficient and friction torque were measured using a developed endpoint detection system, which could measure the friction coefficient, friction torque and downforce during the CMP process[9]. The experimental conditions were as follows. The polishing downforce was 2 Psi; a Cabot iCue 5001 polishing slurry and a polyurethane polishing pad were used; the polished workpiece was a 150 mm diameter Ta wafer on whose surface a Cu layer was electroplated; the rotational speed of the polishing head and the polishing platen were, respectively, 85 r/min and 100 r/min; during the process of wavelet denoising, the db5 wavelet was used; the level number of wavelet decomposition was chosen to be 5; the length of data window was 128; the number of moving samples every time period m was 64; and to avoid the edge effect, the number of delay output samples n was chosen to be 32.

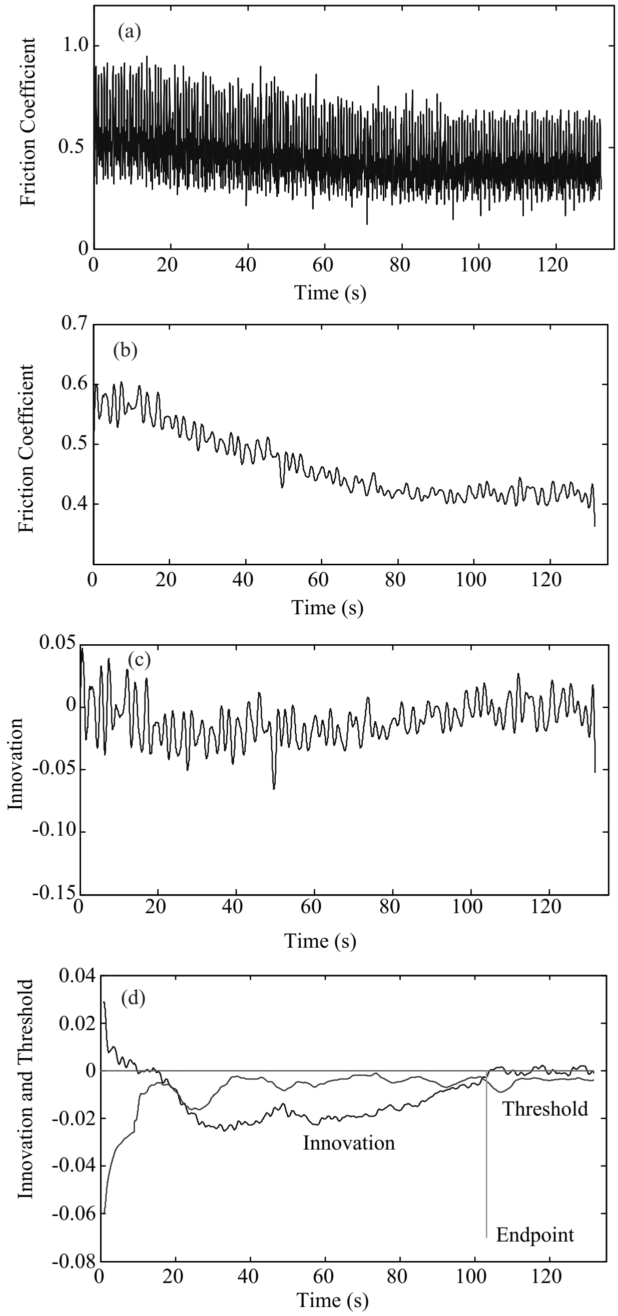

Fig. 6. Results of signal processing during the Cu CMP process. (a) Original signal. (b) Filtered signal. (c) Kalman filter Innovation. (d) Judgment of the CMP endpoint.

Figure 6 shows the original signal, the filtered signal, the Kalman filter innovation and the judgment of the CMP endpoint during the Cu CMP process under the above conditions. From Figs. 6(a), 6(b) and 6(c) it can be seen that the region of the CMP endpoint can be generally indicated by the original signal, the filtered signal or the Kalman filter innovation, but the indications are not explicit enough. The accurate CMP endpoint needs to be determined based on the judgment criteria, as shown in Fig. 6(d). The polished wafer surface was examined using a microscope at different polishing times, and the examination results showed that the method could accurately determine the CMP endpoint. The start time of transiting from Cu to Ta can also be approximately indicated in Fig. 6(d), and the time when the curves of innovation and threshold intersect for the first time is approximately the start time of transiting from Cu to Ta. The transition time was a little long because the workpiece was not the standardized Cu CMP test wafer, and the uniformity of the Cu film was not very good. Similar results can also be obtained for the measured friction torque and the measured data under different processing parameters. Compared with the judging methods based on the frequency domain feature, the signal processing method does not need a very high sampling frequency, and it is easier to realize the real time data processing.

5. Conclusion

A signal processing method for the friction-based endpoint detection system of a CMP process was presented. The signal process method used the wavelet threshold denoising method to reduce the noise contained in the measured signal, extracted the Kalman filter innovation from the denoised signal as the feature signal, and judged the CMP endpoint based on the feature of the Kalman filter innovation sequence. Applying the signal processing method, the endpoint detection experiments during the Cu CMP process were carried out. The results show that the signal processing method can judge the endpoint during the Cu CMP process.

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