Graphical Mapping of AE for Pad Condition Monitoring in Copper CMP

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Chemical mechanical planarization (CMP) of Cu interconnects is a critical bottleneck technology for semiconductor manufacturing at the 65 nm technology node and beyond. The pad condition in CMP is of utmost importance in maintaining acceptable production quality and throughput, as it directly affects many different parameters in CMP including material removal rate (MRR) and process uniformity. Acoustic emission (AE) is a proven technique for *in-situ* monitoring of a wide range of manufacturing processes, and has been demonstrated for the *in-situ* monitoring of various phenomena in the CMP process such as endpoint and MRR detection. A novel graphical mapping approach of sensor signal for monitoring pad condition during Cu CMP is proposed and tested, with AE demonstrating improved sensitivity over that of friction force.

1. Introduction

Chemical mechanical planarization (CMP) is one of the key enabling technologies for the generation of ultrasmooth surfaces in semiconductor manufacturing, and plays a particularly important role in the copper damascene process. While CMP remains as a critical technology for viable semiconductor manufacturing at the 65 nm fabrication node and potentially beyond, it has also become a significant limiting factor for process throughput and quality [1]. There are a significant number of input variables to the CMP process. These include, but are not exclusively limited to: slurry chemicals (pH, concentration, isoelectric point zeta potential, stability of the suspension, etc.), slurry flow rate, abrasive (including hardness, composition, size, shape, concentration), temperature, pressure, velocity and kinematic influences on the velocity of the pad and the wafer, pattern geometries including feature size and pattern density, pad and conditioning, etc., wafer geometry including curvature and mounting, and wafer size [2]. The process outputs of interest to the manufacturer include: polish or material-removal rate (MRR), polish rate of underlying film, planarization rate and "efficiency", polish rate uniformity, feature size dependency with process outputs(polish rate, planarization rate, damage and defects, etc), surface quality including roughness, particles and corrosion resistance, and surface defects, including scratches and contamination [2]. Proper maintenance and stability of these process variables at the local and global scale are critical for maintaining acceptable process throughput. However, all of these parameters are subject to a certain degree of variation over time, with the pad surface condition being a particular factor that can contribute to unacceptable variation in MRR, uniformity, etc. Given the number of process variables in CMP, a reliable and robust means of detecting process variation is of key importance in maintaining stability of the CMP process and acceptable process quality.

In-situ monitoring systems that can be used to characterize, control, and improve the fabrication of semiconductor features are therefore needed to meet increasing demands in precision, throughput, and

quality. It is challenging to integrate traditional quality control and characterization tools (SEM, AFM, XPS, etc) into existing CMP machines, so *in-situ* sensor-based monitoring yields valuable information about the manufacturing process that can serve the multiple purposes of process characterization, control and quality monitoring, and will ultimately be the part of any fully-automated manufacturing environment. When measuring macroscopic phenomena generated by macroscale sources, such as the generation of friction force by overall wafer/pad contact and interaction, conventional sensor technology such as load cells and motor current monitors may be most appropriate. However, for characterizing and detecting material removal at the nanoscale, where sensor signals are generated by highly localized phenomena such as elastic surface asperity interactions and individual dislocation motion, conventional monitoring techniques may not have the necessary signal-to-noise (S/N) ratio and sensitivity required to adequately and reliably characterize surface finish, surface/subsurface defects, and friction force during polishing due to the extremely low forces and power consumption present in CMP. However, acoustic emission (AE) is highly desirable as a viable sensor technology due to its improved sensitivity at the ultraprecision scale when compared to conventional load cell and other technologies, with different levels of AE detectable even at extremely low scales of material removal [3, 4]. As a form of ultrasonic vibration, AE has been established as an effective monitoring tool for factors in CMP such as endpoint detection and material-removal rate, thanks to its increased sensitivity and improved signal-to-noise ratio (relative to other sensor technology) to material removal mechanisms at the micro and nanoscale, including the abrasive mechanisms taking place at the wafer/pad interface [3, 5]. Previous work with AE for endpoint detection in CMP also demonstrated a high degree of sensitivity of the signal to the surface and material properties (hardness in particular) of the polished material [5], but the full range of the capability of AE as a monitoring technique in the CMP operation is still being explored. The relative ease of integration of AE sensors into existing CMP tools makes AE particularly amenable for use as an *in-situ* process monitoring technique.

Hence, the primary purpose of this work is to further investigate to what extent AE can be used to on-line monitor process variation in the CMP operation, with a particular focus on pad surface condition, and serve as a means of *in-situ* characterization and detection of various phenomena taking place at the wafer/pad interface. A novel graphical mapping approach is used as a signal processing technique to visualize pad condition transitions as a function of pad surface condition and slurry type.

2. Experimental Details

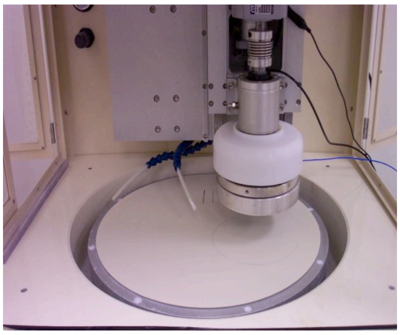
For the CMP operation, a G&P Poli-400 CMP machine was used with a specially designed wafer head for sensor integration. All experiments were conducted with an IC1400 pad with pad conditioning mostly performed in an ex-situ fashion (ie. in between experimental runs). Down pressure was maintained at 2 psi, and a constant pad rotation speed of 60 RPM was used for all experiments. The following sets of experiments were conducted to purposely induce large variation in specific process parameters.

Exp. 1: Continuous polishing for 4.5 minutes with no *in-situ* conditioning.
Exp. 2: Polishing with slurry composition transition, application of *in-situ* conditioning
Exp. 3: Polishing with slurry flow rate transition, application of *in-situ* conditioning

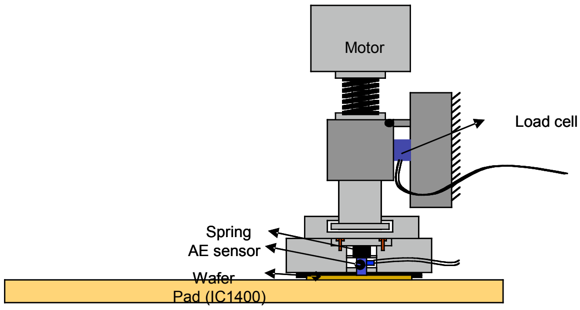
A custom slurry composed of 85 wt% DI water, 10 wt% H_2O_2, 0.1 M of glycine, and 5 wt% alumina abrasive (50 nm average grain size), and was supplied at a constant rate of 110 ml/min (unless otherwise noted). The pad was pre-conditioned with a diamond conditioner before every single experimental run to insure similar initial surface conditions for the pad. A solid 4” diameter oxygen-free high-conductivity (OFHC) Cu block (overall mass ~180 grams) was used to perform these extended polishing experiments that would not normally be possible using conventional Cu wafers, due to the extent of material removal.

Table 1: Experimental Parameters

Machine	G&P Poli-400
Pad	IC1400
Pressure/RPM	2 psi/60 RPM
DAQ Parameters	NI 5102 PCMCIA 100 Hz sampling rate
Load cell	Kistler custom 9137A 20N/volt, 0 – 500 N Resolution : ~0.01N
AE Sensor	DECI SE25 50 kHz highpass filter Pre/post filter amp: 100/50 dB τ_c = 1 msec, 0.02 msec



a)



b)

b)

Fig. 1. a) G&P CMP machine, b) wafer head with integrated AE sensor.

A DECI SE25 AE sensor was used due to its relatively flat frequency response (relative to other commercial sensors) over the 50-500 kHz range. The AE sensor was integrated into the wafer holder, directly coupled to the backside of the wafer with a spring-loading mechanism (see Figure 1b) to minimize signal attenuation. The raw AE signal was preamplified by 50 dB, filtered through a high pass filter at a cutoff frequency of 50 kHz to reduce ambient system noise, and subsequently amplified by another 100 dB. The filtered signal was then processed by a root-mean-square (RMS) filter with time constant of 1 millisecond. A National Instruments DAQScope PCMCIA data acquisition card was used to acquire the signal at a sampling rate of 100 Hz within a Labview software environment, and data postprocessing was conducted with MATLAB and Labview.

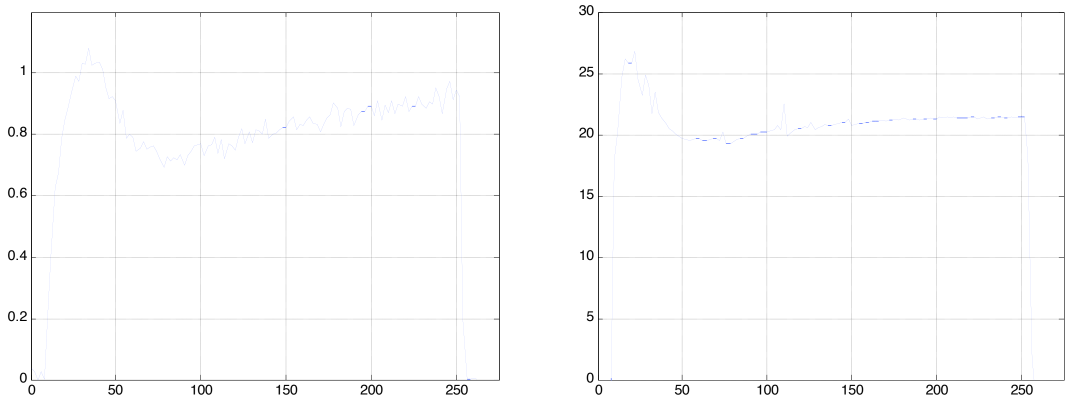
3. Results

3.1. Experiment 1: Continuous Polish

A continuous polish (about 4.5 minutes) of the Cu wafer was conducted without *in-situ* conditioning, and the real-time friction force and AE RMS signal were collected over this duration. Figures 4a and 4b show the resulting AE RMS and friction force measurements over a period of about 4.5 minutes, respectively. As can be seen from these figures, the AE signal demonstrates a marked variation as a function of the initial pad stabilization (as the initial pad asperities are worn down), and overall pad condition. The consistent increase in AE signal over an extended period of

time can be directly attributed to the increase in contact area between the pad and wafer as more pad asperities are worn down. Since the AE RMS signal is proportional to the energy consumed at the wafer/pad interface, the AE signal will scale as a function of contact area and the corresponding increase in physical interaction at the interface. The friction force, however, does not exhibit the same sensitivity

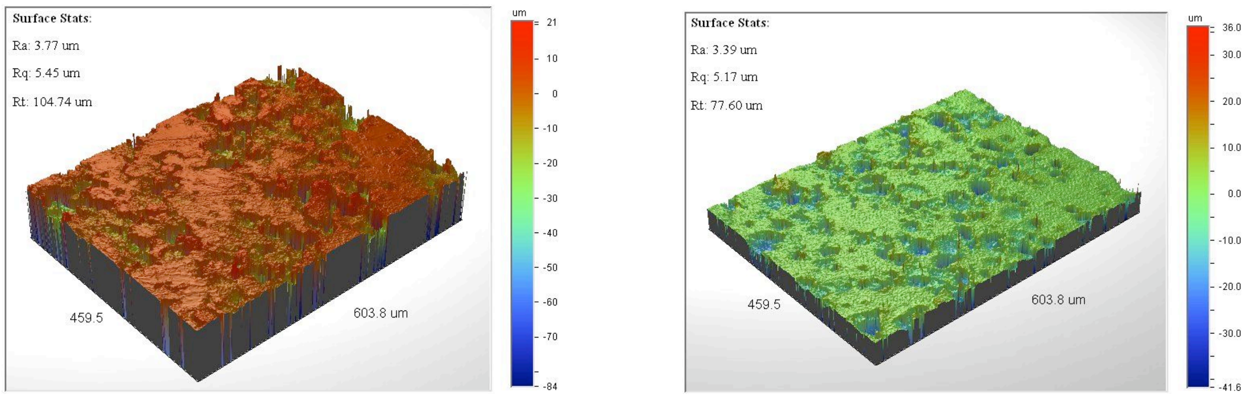
to pad condition as the AE signal does, which demonstrates the improved sensitivity of AE over conventional sensor techniques.



a) b)

Fig. 2. a) AE RMS signal, b) friction force variation over extended polishing time.

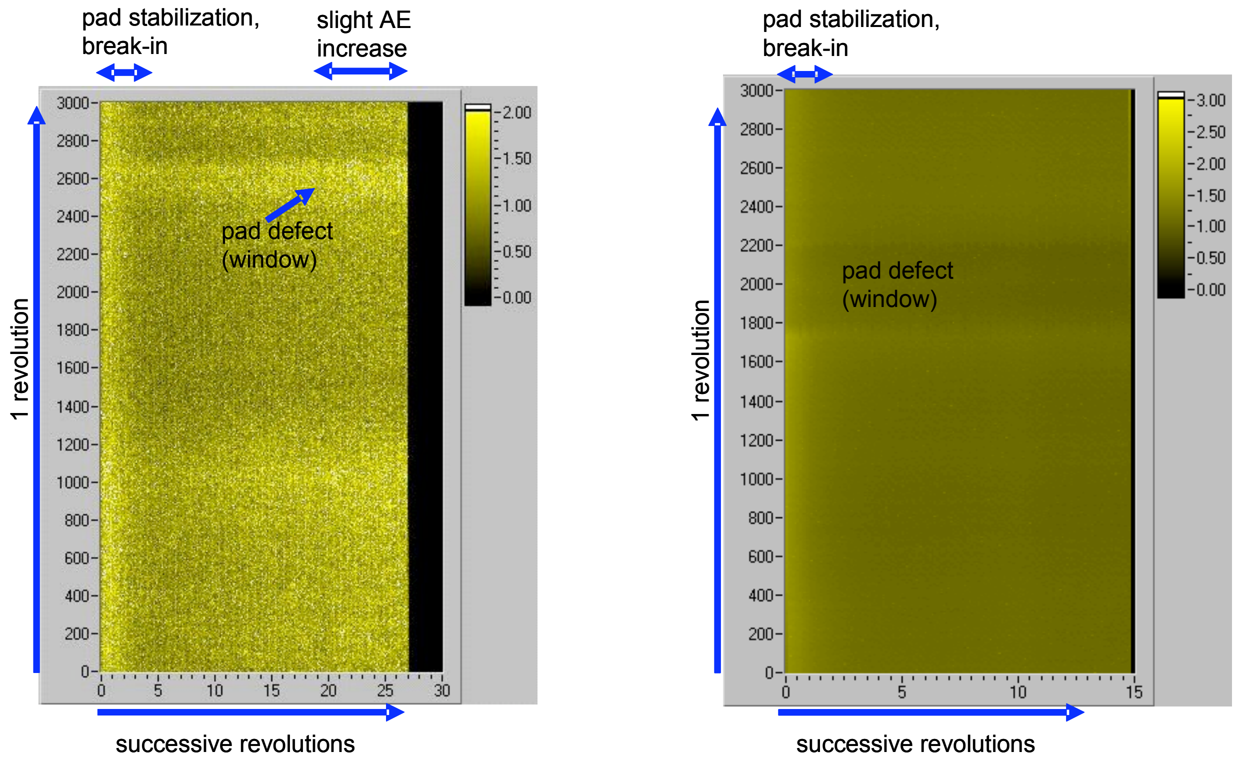
The pad surfaces were characterized both before and after the extended polishing operation with a Wyko white light interferometry-based surface profilometer (see Figures 3a and 3b). Figure 3a shows the freshly-conditioned pad, which exhibits a roughened surface (3.77 µm R_a, 104.7 µm R_t) due to the abrasive action of the diamond grit in the pad conditioner. Figure 3b shows the non-conditioned pad after 4.5 minutes of polishing (3.39 µm R_a, 77.6 µm R_t); note the decrease in R_a and R_{th} surface finish and the smoother, more glazed appearance of the pad due to the lack of *in-situ* conditioning, and resulting asperity flattening. Surface asperities are not as apparent in the non-conditioned pad, and the AE signal demonstrates a much greater sensitivity to this variation in pad topology over that of the friction force.



a) b)

Fig. 3. a) Wyko surface data for freshly conditioned pad,
b) Wyko surface data for non-conditioned pad.

The AE RMS signal as a function of pad rotation and successive revolutions for Experiment 1 (continuous polishing) was plotted on an intensity plot, where black represents a value of zero volts, bright yellow (or white) represents an AE RMS saturation value of 3.5 volts, and intermediate values of AE RMS represented as varying shades of yellow (see Figure 4a). 3000 points of data were taken for each pad revolution (plotted along the ordinate in Figure 4a) over a span of approximately 270 total revolutions (corresponding to a total polishing time of 4.5 minutes, with the AE data for each successive revolution plotted along the abscissa of Figure 4a. The initial pad stabilization (or "break-in") stage can be detected as a region of greater AE RMS intensity along the left part of Figure 4a. Also, the spatial detection of pad defects (in this case, the optical endpoint window on the pad) can be detected as a horizontal band of increased AE intensity. As the pad becomes worn and the contact area increases, the energy consumption at the pad/wafer increases, and manifests itself as a consistent increase in the AE intensity plot when observing from left-to-right. The friction force intensity map is shown in Figure 4b but, with exception to detection of the optical endpoint window on the pad, clearly doesn't demonstrate any marked sensitivity to pad condition, further demonstrating the improved sensitivity of AE for CMP monitoring purposes.



a) b)

Fig. 4. a) AE intensity mapping, b) friction force mapping for extended polishing.

3.2. Experiment 2: Slurry Composition Transition with *In-Situ* Conditioning

The second experiment focused on changing the slurry composition, then applying in-situ conditioning for a specific period of time. After allowing the pad to stabilize after about 2 minutes of polishing, the slurry abrasive size was changed (1 micron average grain size), and a very sharp increase in the AE signal was observed, evidenced by the bright white vertical band in the AE intensity plot in Figure 5. The increase in energy consumption due to the larger abrasive size and increased MRR is reflected in the sharp rise in AE RMS signal. DI water was then introduced into the slurry delivery system afterwards, and a sharp decrease in the AE signal (shown as the darker band adjacent to the region representing the larger abrasive size) was observed, which is

consistent with the lower MRR (and lower energy consumption at the wafer/pad interface). After a minute of polishing with DI water, in-situ conditioning was applied to the pad surface, and the resulting roughening of the pad caused a slight increase in the AE signal, as evidenced as the labeled band in Figure 5. Once the in-situ conditioning was removed, the AE signal then dropped noticeably, demonstrating the usefulness of AE for monitoring variation in the slurry composition, and the presence of conditioning.

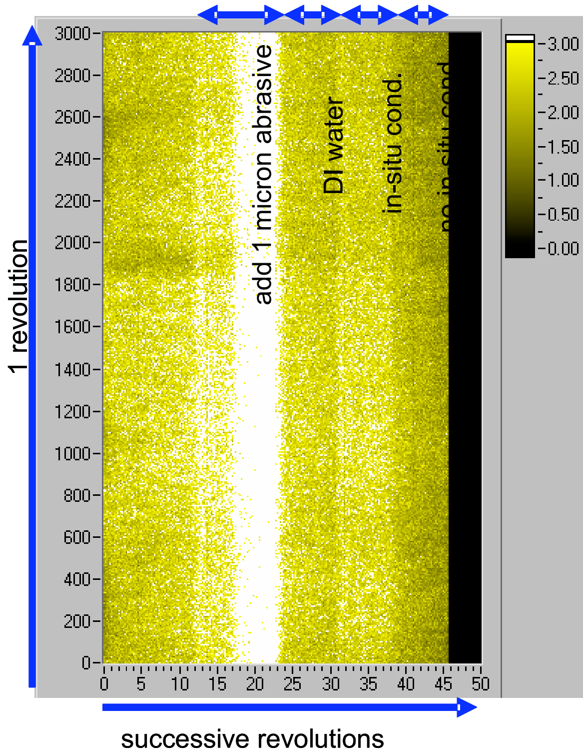


Fig. 5. AE mapping for variation in slurry type and in-situ conditioner application.

3.3. Experiment 3: Slurry Flow Rate Transition with *In-Situ* Conditioning

The third experiment focused on changing the slurry flow rate, then applying in-situ conditioning for a specific period of time. After allowing the pad to stabilize at a slurry flow rate of 110 ml/min, the flow rate was increased to 250 ml/min, but no appreciable change in AE signal could be observed (see Figure 6). It is postulated that above a certain flow rate, the pad/wafer interface is saturated with slurry and no additional variation in sliding characteristics will be observed.. However, below this particular flow rate, the pad/wafer interface will experience a lack of slurry (and resulting fluid lubrication), which will be manifested as an increase in AE signal (as the coefficient of friction between wafer and pad increases due to lack of slurry). After a minute, the flow rate was then lowered to 40 ml/min, and while this variation could not be observed in the friction force signal, a slight increase in AE signal could indeed be seen, attributed to the increase in coefficient of friction, and resultant energy consumption at the pad/wafer interface. In-situ conditioning was then applied to the pad surface, and as before, the resulting roughening of the pad caused a slight increase in the AE signal, as evidenced as the labeled band in Figure 6. Once the in-situ conditioning was removed, the AE signal then dropped noticeably as before. Hence, the AE mapping technique has some limited ability in detecting slurry flow rate and the resulting transition in pad/wafer interaction, although this needs to be explored in further tests.

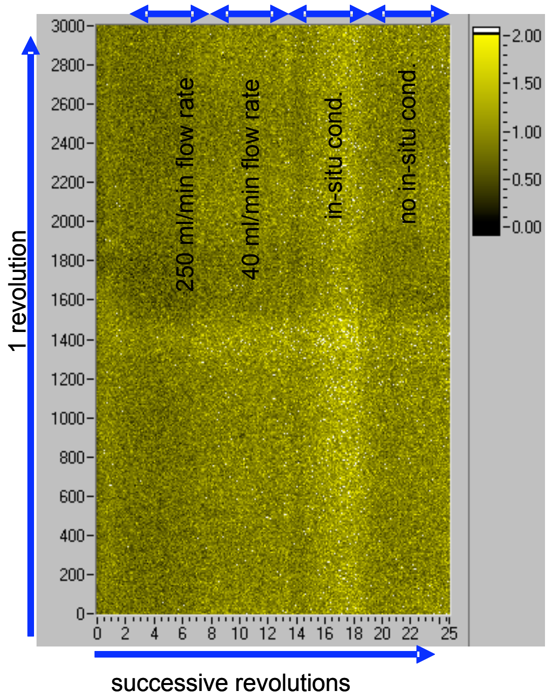


Fig. 6. AE mapping for variation in slurry flow rate and in-situ conditioner application.

4. Conclusions/Future Work

A novel graphical mapping technique has been used to visualize AE signal for in-situ monitoring of process variation and pad condition in a copper CMP operation. The AE signal demonstrated improved sensitivity compared to friction force measurements, with the following observations.

- Initial pad "break-in" and stabilization, and pad topology variation due to application (or removal) of in-situ conditioning can be detected with AE signal. Limited spatial mapping of features in the pad (optical endpoint detection window) is also possible.
- Transitions in slurry type are also detectable with AE, with abrasive size/plain DI water transitions causing variation in the AE signal.
- AE has only limited sensitivity to variations in slurry flow rate, with a slight change observed when transitioning from 110 ml/min to 40 ml/min.

The graphical mapping of AE can be used as an on-line means of detecting pad stabilization, and can potentially be used to detect pad wear (and impending pad "end-of-life"), as well as variations in other process parameters (slurry condition, etc) in an automated production environment. While the sensitivity of AE to process variation in copper CMP has been established, more extensive studies relating AE to other process variables, particularly the presence of process-induced defects (such as scratches) need to be conducted. A more analytical means of characterizing the AE signal and tying it to the sources needs to be found, and will be the focus of future studies.

5. Acknowledgements

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6. References

[1] DeJule, R., "CMP Challenges Below a Quarter Micron", Semiconductor International, pp. 54–60, 1997.

[2] Steigerwald, J.M., Muraka, S.P., Gutmann, R., "Chemical Mechanical Planarization of Microelectronic Materials", Wiley, New York, 1997.

[3] Dornfeld, D.A., Lee, Y., Chang, A., "Monitoring of Ultraprecision Machining Processes," International Journal of Advanced Manufacturing Technology, vol. 21, 2003, pp. 571-578.

[4] Lee, Y., "Monitoring and Planning for Open Architecture Manufacturing of Precision Machining Using Acoustic Emission," Ph.D. Dissertation, Mech. Eng. Department, University of California at Berkeley, 1991.

[5] Lee, D.E., Hwang, I., Dornfeld, D.A., "Precision Manufacturing Process Monitoring with Acoustic Emission," CIRP VIIth International Conference on Monitoring and Automatic Supervision in Manufacturing, Krakow, Poland, August 2004.