Electromagnetic Shielding Effectiveness of Multilayer Metallic Thin Film on Plastic Substrates

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ABSTRACT: Conductive coatings have been applied to plastic substrates to protect electronic devices against electromagnetic interference. A model, based on the transmission line and plane wave theory, is developed to analyze the shielding effectiveness of multilayer metallic thin films. Analyses show that among absorption, reflection, and re-reflection in electromagnetic wave transmission, reflection is dominant, whereas absorption is negligible because of small film thickness. A key indicator of reflection is the thin film's intrinsic impedance characterized by the ratio of conductivity over permeability. Better shielding can be achieved by having the impedance ratio of the adjacent layers higher than 1; i.e., by placing the thin film of higher impedance as the inner layer to the substrate. Without the correct sequence of placement, more layers do not necessarily lead to better shielding. All analytical results are validated by experiments on PC and PP substrates with plasma surface treatment and physical vapor deposition. J Appl Polym Sci 110: 1403–1410, 2008

Key words: EMI; electromagnetic shielding; thin film deposition; impedance match

INTRODUCTION

Most telecommunication systems in use are known to generate radio frequency fields, yet the pervasiveness of mobile phones suggests that users do not in general consider them hazardous, rather they have welcomed the technology into daily lives. The revolution in telecommunications continues with the third generation mobile phone, and further developments will become available in due course. There have been persisting concerns about the possible impact of electromagnetic energy on health. Recent review of scientific developments concluded that biologic and epidemiologic evidence does not necessarily suggest adverse health effect from mobile phone use, but exposure to radio frequency transmissions below the guideline levels may be of some concerns.[1] Because the use of mobile phone is fairly recent, it has not yet been possible to carry out necessary long-term epidemiological studies and evaluate the findings. However, an increase in the risk of acoustic neuromas has recently been reported in Sweden,[2] which may highlight the need for follow-up on phone users, and most importantly, the need in electromagnetic shielding.

In aerospace applications, increasing electronic integrations accentuate the problems of electromagnetic shielding, where the requirement as high as 100 dB is not uncommon. Electromagnetic interference (EMI) is the performance degradation of a device caused by electromagnetic disturbance, which can be a noise, an unwanted signal, or a change in the propagation medium. There have also been ever-increasing regulatory requirements for EMI emissions in electronics packaging by plastic substrates, which are, however, nonconductive and provide no shielding.[3] Shielding by conductive painting, insertion of conducting meshes, injection molding with highly conductive particles/fibers, or electro-less coatings have thus been proposed.[4–6] Conductive paint coating suffers from poor adhesion and the release of volatile organic compounds. Insertion of conducting wire meshes into plastic substrates is not suitable to small, lightweight housings, and is costly and the weight penalty can be substantial. Recent studies also consider polymer with conductive fillers in injection molding by silver powder[7] and nickel powder.[8] Electro-less coatings have also been applied, but the process is time consuming and environmental hazardous.[9] Effective electromagnetic shielding on plastic substrates remains a challenging issue in today's awareness of recyclable products. On comparison, physical vapor deposition is environmental friendly, but the thickness of metallic thin film is often limited to 1 μm.[10] Development of an electromagnetic model to analyze the shielding effectiveness of multilayer thin films is necessary.

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ELECTROMAGNETIC SHIELDING MODEL

Electromagnetic shielding is to reduce the coupling of undesired radiated energy by metallic thin film barrier(s) in the path between the emitter and the receptor. When an electromagnetic wave penetrates through the barrier, both reflection and absorption take place. A portion of the incident waves is reflected from the shielding surface, whereas the remaining penetrates into the barrier. After partial absorption there are successive internal re-reflections at the interfaces of the shielding layers. Consider a uniform plane wave of electric field E and magnetic field H. The Maxwell's equation based on the transmission line theory[11] is

$$\frac{dE}{dx} = -j\omega\mu H \tag{1a}$$

$$\frac{dH}{dx} = -(\sigma + j\omega\varepsilon)E \tag{1b}$$

where μ is the permeability of the material and $\mu = \mu_0\mu_r$. μ_0 is absolute permeability of air ($\mu_0 = 4\pi \times 10^{-7}$ henry/meter) and μ_r is the permeability of the material to air. σ is the conductivity of material in mho/meter. ε is the permittivity of the material and $\varepsilon = \varepsilon_0\varepsilon_r$. ε_0 is the absolute permittivity of air, $\varepsilon_0 = 1/(36\pi \times 10^{-9})$farad/meter and ε_r is the permittivity of the material to air. $\omega = 2\pi f$ and f is frequency in Hz. All homogenous materials are characterized by the intrinsic impedance $\eta = \sqrt{j\omega\mu/(\sigma + j\omega\varepsilon)}$. For dielectric material, the conductivity is extremely small, $\sigma \ll \omega\varepsilon$, and the impedance is

$$\eta = \sqrt{\mu/\varepsilon}. \tag{2a}$$

Conversely, for a conductor operating below the optical frequency defined by $\sigma \gg \omega\varepsilon$, the impedance becomes

$$\eta = \sqrt{j\omega\mu/\sigma} = (1+j)\sqrt{\pi\mu f/\sigma} \tag{2b}$$

and it is characterized by the conductivity and permeability ratio. Defined the propagation constant $\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)}$ to describe the electromagnetic wave. A good conductor is a medium whose $\sigma/\omega\varepsilon \gg 1$ and

$$\gamma = \sqrt{j\omega\mu\sigma} = (1+j)\sqrt{\pi\mu f\sigma} \tag{3}$$

The impedance of an electromagnetic wave is defined by the tangential component of E-field (electric) and H-field (magnetic), $Z = |E|/|H|$. For a homogenous barrier (layer) of thickness t, the impedance is

$$Z = \eta\frac{Z(t)\cosh\gamma t + \eta\sinh\gamma t}{\eta\cosh\gamma t + Z(t)\sinh\gamma t} \tag{4a}$$

$$H(t) = \frac{\eta}{\eta\cosh\gamma t + Z(t)\sinh\gamma t}H(0) \tag{4b}$$

$$E(t) = \frac{Z(t)}{Z(t)\cosh\gamma t + \eta\sinh\gamma t}E(0) \tag{4c}$$

where $Z(t)$ is the impedance at interface t looking into the right of the plane. If $Z(t) \neq \eta$, reflection occurs at the boundary. Let E^i and H^i be the incident electric and magnetic fields, E^r and H^r the reflected fields, and E^t and H^t the transmitted fields. With the continuity of the tangential field components at the boundary, $E^i + E^r = E^t$ and $H^i + H^r = H^t$, the electric and magnetic fields of a plane wave are related by $E^i = \eta H^i$, $E^r = -\eta H^r$, and $E^t = Z(t)H^i$. The reflection coefficients are defined by

$$q_E = \frac{E^r}{E^i} \quad \text{or} \quad q_E = \frac{Z(t) - \eta}{Z(t) + \eta} \tag{5a}$$

$$q_H = \frac{H^r}{H^i} \quad \text{or} \quad q_H = \frac{\eta - Z(t)}{\eta + Z(t)} \tag{5b}$$

and the corresponding transmission coefficients are

$$p_E = \frac{E^t}{E^i} \quad \text{or} \quad p_E = 1 + q_E \tag{6a}$$

$$p_H = \frac{H^t}{H^i} \quad \text{or} \quad p_H = 1 + q_H \tag{6b}$$

For re-reflection effect, the transmission coefficients across the plane are

$$T_H = \frac{H(t)}{H^i} \tag{7a}$$

$$T_E = \frac{E(t)}{E^i} \quad \text{or} \quad T_E = \frac{Z(t)}{Z_w}T_H \tag{7b}$$

where $E(t)$ and $H(t)$ are the values at the interfaces. Z_w is the impedance of the incident wave. Substituting eqs. (5) and (6) into eq. (7)

$$T_H = p_H(1 - q_H e^{-2\gamma t})^{-1}e^{-\gamma t} \tag{8a}$$

where

$$p_H = \frac{4Z_w\eta}{(z_w + \mu)(Z(t) + \eta)} \quad \text{and}$$
$$q_H = \frac{(Z_w - \eta)(Z(t) - \eta)}{(Z_w + \mu)(Z(t) + \eta)} \tag{8b}$$

When $Z(t) = Z_w$, $p_H = -4k/(k+1)^2$, $q_H = (k-1)^2/(k+1)^2$, and $k = Z_w/\eta$, eq. (8a) can be rewritten by dropping the subscript

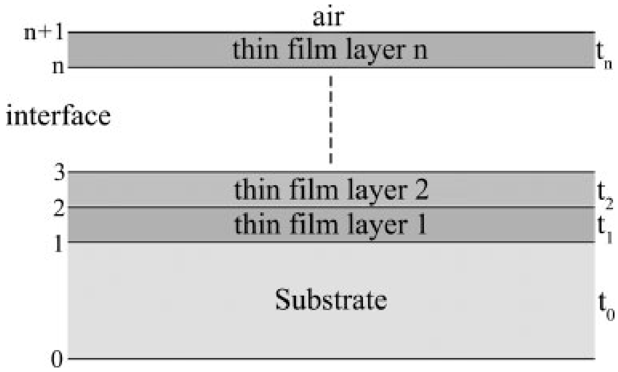

Figure 1 An illustration of multilayer shielding.

$$T = p(1 - qe^{-2\gamma t})^{-1} e^{-\gamma t} \tag{9}$$

The total shielding effectiveness (SE) is defined by

$$\mathrm{SE} = -20\log_{10}|T| \tag{10}$$

It is the sum of the absorption $\alpha_A = 20\log_{10}|e^{-\gamma t}|$, the reflection $\alpha_R = 20\log_{10}|p|$ and the re-reflection $\alpha_B = 20\log_{10}|1 - qe^{-2\gamma t}|$.

Practical shielding depends on a number of parameters such as frequency, distance of interference source from the shielding layers, polarization of the fields, and discontinuities in a shield. In EMI, electromagnetic waves can be regarded as plane waves, and interference should consider both electric and magnetic effects. For multilayer shielding as illustrated in Figure 1, there are n layers, each of thickness t_i and $n + 1$ interfaces. The transmission line theory requires the continuity of the electric and magnetic field at each interface (boundary), and the impedance of a homogenous thin film of thickness t_i can be written by

$$Z_i = \eta_i \frac{Z(t_{i-1})\cosh\gamma_i t_i + \eta_i \sinh\gamma_i t_i}{\eta_i \cosh\gamma_i t_i + Z(t_{i-1})\sinh\gamma_i t_i} \tag{11}$$

$i = 1\ldots n$, where η_i, γ_i, and t_i are the intrinsic impedance, propagation constant, and thickness of the ith layer, respectively. η_0 and γ_0 is that of the substrate, respectively. $Z_0 = 377\ \Omega$ and Z_i is the impedance at interface t_i looking into the right of the plane. If $Z_i \neq \eta_i$, reflection occurs at the interface. The transmission coefficient in eq. (9) for multilayer becomes

$$T = p\left[(1 - q_0 e^{-2\gamma_0 t_0})(1 - q_1 e^{-2\gamma_1 t_1})\cdots(1 - q_n e^{-2\gamma_n t_n})\right]^{-1} \times e^{-\gamma_0 t_0 - \gamma_1 t_1 - \cdots - \gamma_n t_n} \tag{12a}$$

where

$$p = \frac{2.Z_w 2\eta_0.2\eta_1.2\eta_2\cdots 2\eta_n}{(Z_w + \eta_0)(\eta_0 + \eta_1)(\eta_1 + \eta_2)\cdots(\eta_n + Z_w)} \tag{12b}$$

$$q_i = (\eta_i - \eta_{i-1})(\eta_i - Z_{i+1})/(\eta_i + \eta_{i-1})(\eta_i + Z_{i+1}) \tag{12c}$$

The total shielding effectiveness is composed of the absorption (α_A), reflection (α_R), and successive internal re-reflection (α_B). The absorption of the n layers is the attenuation

$$\alpha_A = 20\log_{10}\left|e^{\gamma_0 t_0 + \gamma_1 t_1 + \cdots \gamma_n t_n}\right| \tag{13}$$

the total reflection can be expressed as the sum of the reflection at each interface,

$$\alpha_R = 20\log_{10}\left|\frac{1}{2^n}\left(1 + \frac{\eta_0}{Z_w}\right)\left(1 + \frac{\eta_1}{\eta_0}\right)\cdots\left(1 + \frac{Z_w}{\eta_n}\right)\right| \tag{14}$$

and the successive internal re-reflection is

$$\alpha_B = 20\log_{10}\left|(1 - q_0 e^{-2\gamma_0 t_0})(1 - q_1 e^{-2\gamma_1 t_1})\cdots (1 - q_n e^{-2\gamma_n t_n})\right| \tag{15}$$

ANALYSIS OF SHIELDING EFFECTIVENESS

Electromagnetic shielding of a single metallic thin film layer is mainly determined by the boundary condition. In the space adjacent to the thin film layer, the reflected electric field is tangential and vanishing small, whereas the magnetic field is also tangential but with a local maximum. The absorption in eq. (13) is proportional to the propagation constant γ_i, hence to ($\sigma_i\ \mu_i$), and to film thickness t_i. However, the reflection in eq. (14) is independent of the film thickness and is characterized by the impedance ratio of two adjacent layers. The internal re-reflection, similar to absorption, depends not only on the permeability and conductivity but also on the thin film thickness.

The above analysis indicates that thin film metallic layer, though widely used in shielding, is not for absorption but it is for reflection. Figure 2(a,b) show the absorption and reflection of a single thin film layer on a substrate. The absorption (in dB) is linear to the propagation constant, while reflection, at substantially higher dB level, is an exponential function of the intrinsic impedance. Thin film of high impedance, i.e., high conductivity and low permeability, is therefore desirable. Table I shows that the metallic thin film is applicable to electromagnetic shielding. Conductivity and permeability are functions of temperature and frequency. Above a few hundred kHz, the relative permeability approaches 1. For this reason, shielding by the same thickness of magnetic materials depends only on frequency. Nonmagnetic materials, except silver, have $\sigma\mu < 1.0$ indicating

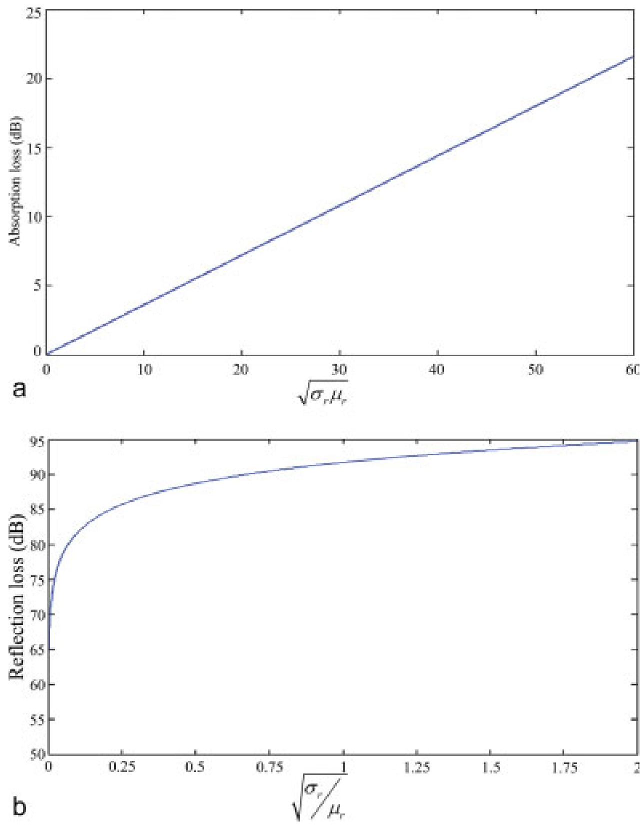

Figure 2 (a) The absorption and (b) reflection for plane wave at 300 MHz.

poor absorption. All magnetic materials such as nickel and steel are, by comparison, good absorbers at low frequencies because $\sigma\mu > 2$; however, nonmagnetic materials outperform all magnetic materials in reflection, and hence in shielding effectiveness. Aside from oxidation concern, silver and copper are preferable.

Skin depth is the traveling distance of the wave as it decreases in magnitude e^{-1} of its original value where e is exponential term, and it is given by

$$\delta = \frac{1}{\alpha} = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{16}$$

In an electrical thin film when the thickness is thinner than its skin depth, the depth of penetration of the wave traveling is a function of frequency, permeability, and conductivity. As skin depth is reduced by $\mu\sigma$, an obvious way to reduce skin depth for better shielding effectiveness is by increasing either the conductivity or permeability. But such measures only works in "thick" coating layer. Table II illustrates the shielding effectiveness as a function of thickness and frequency for a single copper layer and a single nickel layer. Skin depth in kHz to GHz range is more than 2 μm, which is higher than the layer thickness by physical vapor deposition. Shielding for EMI is strongly dependent on the frequency range of interest as indicated in eqs. (2) and (3), and the effectiveness is mainly dominated by the reflection at the interface of the metallic layer. Absorption, by comparison, though proportional to the propagation constant, is negligible. In single layer shielding, better effectiveness is by having the material of higher intrinsic impedance, and nonmagnetic materials are desirable because they outperform nearly all magnetic materials. Reflection is the prime mechanism in shielding effectiveness, and according to eq. (14) it is independent of film thickness but dependent on the material properties. For example, a single layer of 300 nm aluminum on PC substrate can provide about 60 dB shielding at 900 MHz, mainly by reflection. In many applications, weight saving is an important consideration, and thinner layers having good shielding effectiveness is desirable.

The effect of reflection to electromagnetic shielding becomes more prominent as the number of layers increases. Consider one and two layer shielding of the same total thickness 300 nm. The difference of absorption between one and two layers shielding is $\Delta\alpha_A = 8.686(t_2\ (\alpha_2 - \alpha_1))$ where α_i is defined in eq. (16) for the ith layer and because t_2 is very small, the difference is negligible. Reflection can be calculated by eq. (14) and the difference between one and two layers shielding is $\Delta\alpha_R = 20\log_{10}|(1 + \eta_1/\eta_2)/2|$. Figure 3 shows the improvement of shielding effectiveness by having the second metallic layer. When the impedance ratio of the two layers is smaller than 1, $\eta_2/\eta_1 < 1$ or $(\sigma_1/\mu_1)/(\sigma_2/\mu_2) < 1$, the metal-to-metal interface leads to adverse reflection and lower shielding effectiveness. This second layer is therefore counter productive in this case. More metallic thin film layers do not necessarily lead to better shielding. The two layers should be deposited in correct sequence (order) of substrate/high-impedance/low-impedance so as to improve shielding effectiveness. For example, the two layers shielding by $t_1 = 200$ nm aluminum and $t_2 = 100$ nm nickel in substrate/Al/Ni can provide 64 dB, about 3–4 dB increase when compared with that from a single aluminum layer of the same total thickness. Improvement of more than

TABLE I
Relative Conductivity and Permeability of Materials at 1 KHz

Material	σ	μ	σ/μ	μσ
Silver	1.05	1	1.05	1.05
Copper	1	1	1	1
Aluminum	0.61	1	0.61	0.61
Nickel	0.23	100	2×10^{-3}	23

TABLE II
Shielding Effectiveness (SE) at Film Thickness 10 μm and 100 nm

Material	Copper		Nickel	
Frequency	1 (kHz)	1 (GHz)	1 (kHz)	1 (GHz)
Skin Depth (μm)	2100	2.1	4800	4.8
α_A (100 nm)	4.2×10^{-4}	0.4156	0.0019	0.1859
α_R (100 nm)	135.6826	75.6832	108.6930	68.6942
α_B (100 nm)	−74.9003	−15.3382	−61.8598	−22.0671
SE (100 nm)	60.7827	60.7606	46.8350	46.8130
α_A (10 μm)	0.0416	41.5629	0.1859	18.5875
α_R (10 μm)	135.6826	75.6832	108.6930	68.6942
α_B (10 μm)	−34.9493	2.4417	−22.0830	2.4917
SE (10 μm)	100.7749	119.6878	86.7958	89.7734

20 dB is possible as indicated in Figure 3. For reflection by thin film layer(s), there must be mobile carriers (electrons or holes) to interact with the electromagnetic fields, and thus electrical conductive thin films are preferable. Conventional wisdom assumes that the shielding effectiveness is simply because of the combined effects of the two layers: the magnetic layer contributing magnetic reflection at low frequency, the conductive layer providing conducting reflection at higher frequency. The above analysis indicates otherwise. Alternating conductive and permeable layers have profound impact on shielding effectiveness.

Consider three-layer shielding by copper, aluminum, and nickel, each of 100 nm thickness. Their intrinsic impedance is 1, 0.61, and 0.002, respectively. Table III lists the shielding effectiveness in different layer sequence. The results validate that substrate/Cu/Al/Ni has the best shielding because the thin films follow the condition that the impedance ratio of the adjacent layers is higher than 1. Conversely, inadequate layer sequence such as substrate/Ni/Al/Cu is the worst by more than 6 dB.

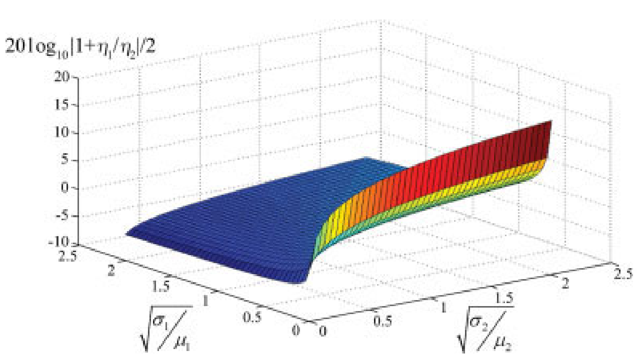

Figure 3 The increase of shielding effectiveness at 900 MHz by having a second layer. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com].

EXPERIMENTAL VERIFICATION OF SHIELDING EFFECTIVENESS

In experimental verification, the surface activity of the polymer substrate is low so that adhesion at the metal/polymer interfaces shall be improved before metallic thin film deposition.[12] Metallization of the polymer substrates is a two-step process: substrate pretreatment and metallic thin film deposition. Plasma surface treatment was applied to polymer substrate (PC and PP) to improve mechanical anchorage by increasing chemisorbed catalyst. Low-temperature reactive plasma treatment by oxygen was selected and the substrates' surface characteristics were analyzed by X-ray photoelectron spectroscopy and atomic force microscopy (AFM, NT-MDT/P47E10 P7LS dry type). Figure 4 shows the images obtained through AFM of the PC and PP substrate surface before and after treatment. The average roughness of PC surface increased from 5.28 to 9.55 nm by plasma treatment. Similarly, on PP surface from 15.2 to 23.9 nm.

Different single layer and multilayer shielding of aluminum and nickel are selected to verify the analyses. The metallic layers are deposited by physical vapor deposition (PVD), where the substrates were mounted a holder rotating at 40 rpm in a vacuum chamber about 5×10^{-6} torr. The periodic exposure to the vapor efflux prevents over heating of the

TABLE III
Shielding Effectiveness (SE) at 900 MHz With Each Layer of 100 nm

Thin film layers	SE(dB)
Substrate/Cu/Al/Ni	67.3004
Substrate/Cu/Ni/Al	67.0747
Substrate/Al/Cu/Ni	67.1214
Substrate/Al/Ni/Cu	62.6834
Substrate/Ni/Cu/Al	64.7640
Substrate/Ni/Al/Cu	60.6003

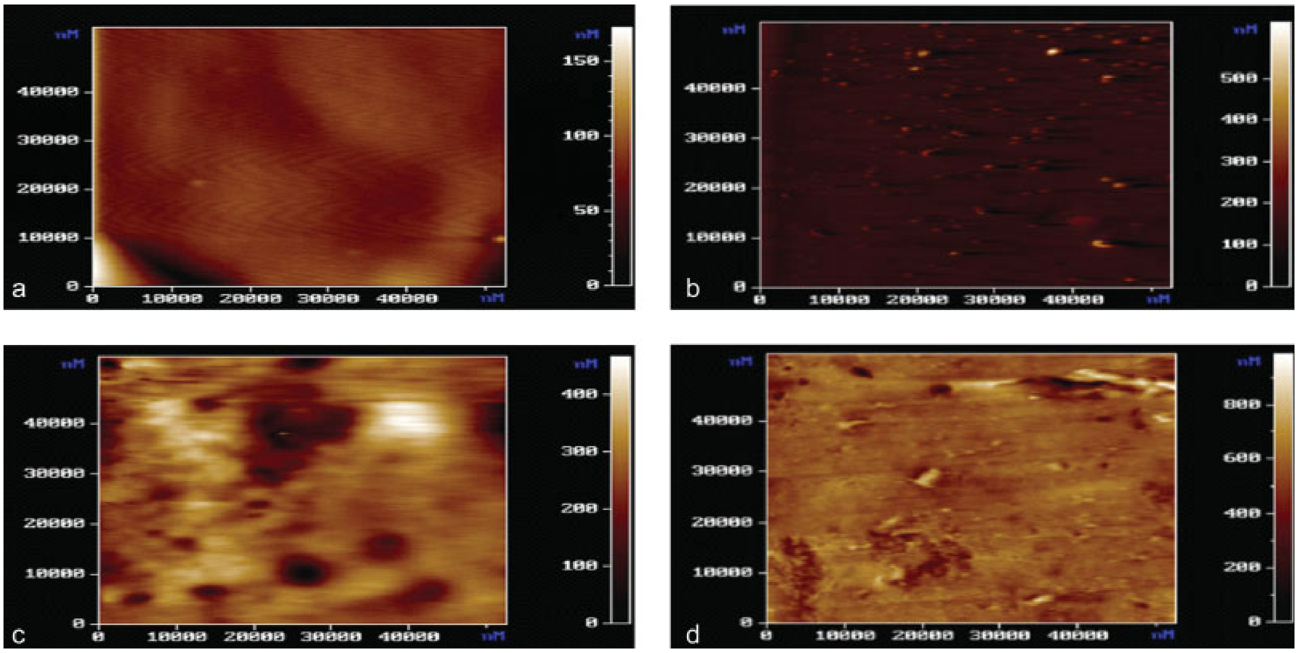

Figure 4 AFM image of the substrate surface before and after plasma pretreatment. (a) PC, before, $R_a = 5.28$ nm (b) PC, after, $R_a = 9.55$ nm (c) PP, before, $R_a = 15.2$ nm (d) PP, after, $R_a = 23.9$ nm. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com].

samples and the estimated chamber temperature was about 40°C. Since aluminum has low melting point at 660°C, the deposition rate should be decreased to avoid overheating of the target. Nickel has high melting point at 1453°C, but low deposition rate is still desirable for the low glass transfer temperature of plastic substrates. The target materials of both aluminum and nickel were 99.99% pure.

The adhesion of the thin film layer on the substrates is measured by ASTM D3359-02[13] and the shielding effectiveness is examined by ASTM D4935-99.[14] The experiment includes five test samples as listed in Table IV. Test 1 and 2 are to deposit 100 nm aluminum and nickel, respectively, for comparing different conductivity and permeability. Test 3 is to deposit 300 nm aluminum on substrate. Test 4 is with aluminum layer $t_1 = 200$ nm and nickel layer $t_2 = 100$ nm. Test 5 is the 2-layer in reverse order to verify the difference from reflection and internal re-reflection. ASTM D4935 is used to characterize the shielding performance of a plane sample against a transverse electromagnetic wave in 30 MHz to 3 GHz. The results in test 1 and 2 as listed in Table IV validate that for a single layer shielding of the same thickness (100 nm in this case), thin film material with higher intrinsic impedance and thus higher conductivity has better shielding, aluminum film is superior to nickel because of better conductivity as predicted in eq. (14), and the shielding effectiveness is proportional to film thickness. The two-layer shielding of total thickness 300 nm in substrate/Al/Ni outperforms single layer aluminum by more than 3 dB. The reverse layer sequence in test 5 validates that more layers do not necessarily lead to better shielding. In conclusion, multilayer thin film is, in general, superior to single layer in shielding effectiveness, provided the layers are arranged to have the intrinsic impedance ratio of the adjacent layers higher than one.

The discrepancy between simulation and experiment in Table IV may come from many causes. The pressure of vacuum chamber, the deposition rate,

TABLE IV
Shielding Effectiveness (dB) by Experiments and Simulation

Thin film	1 Substrate/Al ($t = 100$ nm)	2 Substrate/Ni ($t = 100$ nm)	3 Substrate/Al ($t = 300$ nm)	4 Substrate/Al/Ni ($t = 200/100$ nm)	5 Substrate/Ni/Al ($t = 100/200$ nm)
900 (MHz)	44.91	39.17	48.55	52.24	46.71
1.80 (GHz)	46.62	41.42	48.63	54.89	46.13
2.45 (GHz)	46.96	41.60	48.74	54.78	46.45
Simulation at 900 (MHz)	56.48	47.25	60.26	63.57	58.45

and the stability of the power may result in different deposition quality, and pseudohomogeneous thin film with some holes, slits, or other apertures are inevitable. The electrical properties of a pseudohomogeneous metallic thin film are usually measured in unit of either surface resistance or volume receptivity. Alpha step profilometer (α-step) is used to measure the film thickness and scanning electron microscope (SEM) to check the individual layer thickness in multiplayer coatings. Variation of the deposition and the layer thickness is within 15%. The ideal conductivity of aluminum thin film is 3.54 $\times$ 10^7 mhos/meter; however, the conductivity of 115 nm aluminum (100 nm target thickness) on a PC substrate is only 4.95 $\times$ 10^5 mhos/meter as measured by a four-point probe. Thin film of adequate thickness is thus necessary to have bulk-like conductivity. Another verification shows that the aluminum thin film of 296 nm (300 nm target) on PC has the conductivity of 3.23 $\times$ 10^6 mhos/meter. Too thin a film by physical vapor deposition can decrease the conductivity by more than one order.

It should be noted that the different surface resistivity implies different deposition condition compared with bulk material. XRD is used to characterize the deposited thin films, and the results in Figure 5 illustrate that the (111), (200), and (220) peaks, each representing the preferred orientation, can be seen in aluminum thin films and the (010), (011), and (200) peaks in nickel thin films. The peak intensity supports the results of surface resistivity measurements. Numerical calculations by using the measured conductivity match the experimental results. Increasing the film thickness to minimize its conductivity degradation is necessary to reach desired shielding.

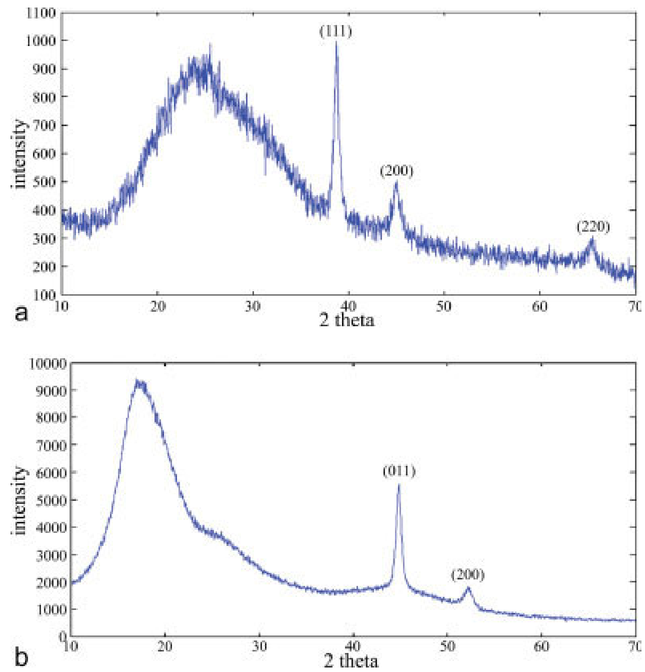

Figure 5 XRD test results for (a) aluminum and (b) nickel thin film deposition.

CONCLUSIONS

1. A model of electromagnetic shielding effectiveness based on the transmission line and plane wave theory is developed for multilayer-metallic thin films on plastic substrates. The total shielding effectiveness is composed of absorption (α_A), reflection (α_R), and successive internal re-reflection (α_B). Analyses show that shielding provided by absorption is negligible because of limited film thickness, while reflection is dominant. The reflection mechanism in multilayer is critical to effective electromagnetic shielding.
2. Multilayer provides better shielding when compared with single layer of the same total thickness; however, the layer sequence is critical. Better shielding can be achieved by placing the thin film of higher intrinsic impedance closer to the substrate and by placing the thin films in a sequence for impedance ratio higher than 1. For same total thickness of 300 nm, the two-layer shielding by aluminum and nickel can provide 64 dB, about 3–4 dB improvement when compared with that from single aluminum layer of the same thickness. All analytical results are validated by experiments. The electrical properties for the pseudohomogeneous metal coatings are measured in surface resistance by a four-point probe. Thin film of adequate thickness is necessary to have bulk-like electrical properties. This study is limited to electromagnetic shielding on plastic substrates by metallic thin films from physical vapor deposition. Comparison of shielding effectiveness with conductive polymers and polymers composites containing conductive particles/fibers may have to be carefully examined as the volume/weight ratio of the conductive fillers to the host substrate may be of significance. It is generally accepted that from the view point of implementation, recyclability, and cost-effectiveness, multilayer thin film deposition is desirable.
3. Conventional practice in quantifying electromagnetic shielding effectiveness of a plastic casing in electronic devices, e.g., notebook computer and mobile phone, is to measure the surface resistance of the metallized substrate. It

is thus often assumed that lower resistance on the top layer is preferable. This practice and assumption is valid only to single layer shielding. Multilayer shielding can achieve better shielding; however, the surface resistance of the top layer—only the top layer is measurable—is by no means a valid indicator of shielding effectiveness. It is the reflection mechanism at the layer interfaces that dominates the shielding. Substrate/Cu/Al/Ni has much higher shielding than substrate/Ni/Al/Cu, but the surface resistance of the former is for sure smaller than that of the latter. Similarly, the shielding effectiveness of substrate/Al/Ni is better than that of substrate/Ni/Al. Surface resistance is not a reliable measure in predicting electromagnetic shielding by multilayer.

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