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Electromagnetic Scattering of Two-Dimensional Electronic Systems

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ABSTRACT In this paper, we use the surface equivalence theorem and boundary conditions to develop a set of integral equations to study the electromagnetic (EM) scattering from thin material sheets. The proposed scheme is well-suited for EM investigation of two-dimensional (2D) materials that are increasingly becoming key components in the development of terahertz (THz) frequency devices. We also discuss the electronic properties of 2D materials that control the EM scattering, out of which existence of plasma waves at THz frequencies is most significant. Finally, the far-field scattering response for infinitesimally thin 2D materials is presented.

INDEX TERMS Two-dimensional materials, electromagnetic scattering, antennas for terahertz applications, thin sheets, boundary conditions.

I. INTRODUCTION

with the emergence of high-precision nanoscale fabrication techniques, we have seen great interest in the synthesis of low dimensional materials, which demonstrate extraordinary electronic properties. A distinctive feature of two-dimensional materials that are only a few nanometers thick is that the electron motion does not face any resistance in a two-dimensional plane.

In solid-state devices such as a high-electron mobility transistor (HEMT), plasma waves can be generated through current-driven instabilities [1]. This phenomenon has led to some breakthrough achievements in the THz frequency region [2]–[8]. The underlying physics addresses the behavior of the two-dimensional electron gas (2DEG), which is formed at the interface of two semiconductor materials that have slightly different band gaps. In a transistor fabricated by epitaxially depositing multiple layers of semiconductor materials, free electrons tend to accumulate when a 2DEG region is surrounded by gate, source and drain terminals, thereby creating a transistor channel. In addition to the unusually high electron mobility, the electron densities that are observed in a 2DEG are comparable to metals. Moreover, there is no need to intentionally dope the semiconductor stack to achieve these extraordinary electronic properties. Remarkably, with the aid of external electromagnetic radiation, plasma waves can be generated in a field-effect transistor channel which is only a few atoms thick. This phenomenon was first observed more than 40 years ago [9], [10]. Another interesting feature of a 2DEG is that the frequency response of the generated plasma waves can be tuned through external voltage bias [11], [12]. Plasma wave based systems are increasingly becoming pivotal in the development of components that couple energy with nanostructures, and in which the energy can be localized to only a few nanometers. However, acceptable efficiencies of such systems, that include photo-conductive antennas in the THz frequency range, can only be obtained at very low temperatures. To overcome this drawback, not only must new materials be developed, but new designs also need to be investigated, in which the wave analysis plays a pivotal role.

Numerical electromagnetic (EM) analysis for thin conducting sheets is considered challenging as a highly refined mesh is required to accurately resolve the structural details. Historically, approximation methods with approximate boundary conditions (BC) are used in this regard, out of which the Leontovich BC [13], [14] is most well-known. The Leontovich BC relates the tangential electric and magnetic fields on the surface of the object as,

$$\mathbf{E}_{tan} = Z\,\hat{\mathbf{n}} \times \mathbf{H}, \tag{1}$$

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where Z is the surface impedance and $\hat{\mathbf{n}}$ is the outward unit vector, normal to the surface. Although, the expression in (1) appears to be fairly simple, its accuracy is governed by the material properties as well as the physical complexity of the object. There have been several studies that modify (1) in order to gain a form applicable to extremely thin and conductive sheets. In one study involving zero-thickness structures [15], the revision entailed introducing an additional term that incorporates properties of the associated dielectric material. Resistive boundary conditions were introduced in [16] in which a two-media EM scattering configuration was converted to a single medium scattering problem. Other techniques addressing the scattering properties of thin sheets are based upon the Nystrom method, in which a discretization scheme is used to model the structure [17]. Although Nystrom method based techniques are fast, they often suffer from a lack of accuracy, especially at low discretization orders.

In this paper, we develop a mathematical framework for investigating the scattering response of an infinitesimally thin flat layer of a conductive element such as a 2DEG, a plasma or a simple conductor. Here we extend an earlier formulation introduced [18], [19]. We assume initially that the conductive sheet is surrounded by free-space. We then use the surface equivalence theorem to obtain the electric and magnetic field expressions for the interior and exterior equivalent problems. The paper is structured as follows. In Section II, we first present the dispersion relation for a 2DEG and discuss the electronic properties of plasma created in solid-state devices. We then introduce the integral equation based formulation for determining the scattering response. Section III shows our numerical results with other similar techniques. Conclusions are summarized in Section IV.

II. THEORY

A. DISPERSION RELATION

It is now well-known that in an epitaxially grown solid-state device such as HEMT, a 2DEG is formed which when biased, acts as a transistor channel upon biasing. When the source and drain terminals of the transistor are biased and the desired Dyakanov boundary conditions [4], [5] are established across the channel, the current driven in the channel leads to the generation of plasma waves. A cavity is formed in the channel owing to wave reflections from the conducting boundaries, thereby setting up a standing wave current in the channel. In the event of an instability, these standing waves radiate at a frequency which lies in the THz (0.1 −10 THz) range. Plasma wave instability is known to be the first mechanism behind the generation of THz radiation [11], [20], [21].

Plasma waves have wavelengths that are much shorter than their the free-space counterpart. The dispersion relation describes this compressed wave nature. Let us consider a HEMT structure surrounded by free-space, and excited by a TM polarized plane wave. To formulate the dispersion equation, we use an equivalent transmission line analogue of the multilayer semiconductor stack of the transistor [22], [23]. In a circuit form, the 2DEG is described by a shunt admittance, which in fact, is a frequency dependant, Drude-type surface conductivity [24],

$$Y_\sigma = \sigma_s = \frac{N_s e^2 \tau}{m^*}\frac{1}{1+j\omega\tau}, \tag{2}$$

in which the sheet charge density is expressed as N_s, e is the elementary charge, τ is the relaxation time and m^* is the effective electron mass in the 2DEG. The transverse resonance condition is employed to obtain the equivalent TL circuit, expressed as [25],

$$Y^\uparrow(z_0) + Y^\downarrow(z_0) + Y_\sigma = 0 \tag{3}$$

in which $Y^\uparrow(z_0)$ and $Y^\downarrow(z_0)$ are respectively the up- and down-looking TL admittances,

$$Y^\uparrow(z_0) = Y_2\frac{1-\Gamma^\uparrow(z_0)}{1+\Gamma^\uparrow(z_0)}, \tag{4a}$$

$$Y^\downarrow(z_0) = -jY_1\cot(k_{z1}h), \tag{4b}$$

as seen from the plane of the 2DEG, assumed to be at $z = 0$. For each layer, Y_i and k_{zi} where $i = 0, 1, 2$ are the respective TM mode admittance and transverse wavenumber of free-space, barrier and substrate layers respectively given by:

$$Y_i = \frac{\omega\varepsilon_i\varepsilon_0}{k_{zi}}, \quad k_{zi} = \pm\sqrt{k_0^2\varepsilon_i - k_x^2} \tag{5}$$

where ε_i is the relative permittivity of i^{th} layer and k_x is the longitudinal propagation constant of the structure. The upward-looking reflection coefficient $\Gamma^\uparrow$ in (4a) is expressed in terms of the TM mode admittances,

$$\Gamma^\uparrow(z_0) = \frac{Y_1 - Y_0}{Y_0 + Y_1}\mathrm{e}^{-2jk_{z2}d_1} \tag{6}$$

A closed-form expression for the longitudinal propagation constant k_x obtained by solving (3) is tedious, therefore, numerical root-finding techniques such as the Newton method [26] have to be employed. As an example, we consider a back-gated transistor consisting of GaN/AlGaN heterostructure, in which the spacing between the gate and channel is $d = 100\,\text{nm}$. The length L of the channel is $2\,\mu\text{m}$ while the AlGaN barrier layer is $h = 20\,\text{nm}$ thick. The permittivity of both semiconductor layers is approximated to the static value, i.e., $\varepsilon_1 \approx \varepsilon_2 = 9.5$ when the mole-fraction of aluminum in AlGaN alloy is 0.2. Following the measured values as described in [27], N_s is $5 \times 10^{13}\,\text{cm}^{-2}$, while τ has a value of 114 ps at 3 K. As the temperature is increased, τ gets smaller which leads to reduced mobility and introduces loss in the channel. Interestingly, N_s can be controlled through the gate voltage V_G, which finds application in developing tunable detectors and antennas. In terms of V_G we have,

$$N_s = N_0 \times \left(1 - \frac{V_G}{V_T}\right), \tag{11}$$

in which N_0 is the zero-bias density and V_T is the gate threshold voltage of the transistor. For a channel terminated by highly conducting source and drain terminals at each side,

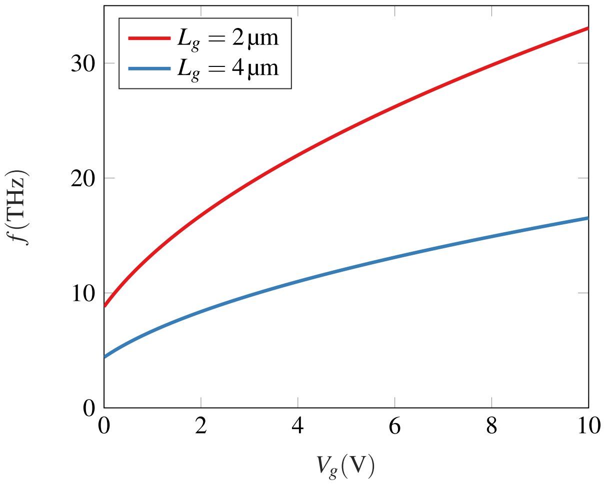

FIGURE 1. Plasma wave dispersion diagram for a transistor structure supporting a 2DEG channel.

the resonant frequency as a function of carrier density is expressed as [28]:

$$\omega = \sqrt{\frac{N_s e^2 d}{m_* \varepsilon}} \frac{\pi}{L} \tag{12}$$

where ε is the average permittivity of the surrounding media. Using (11) and (12), the tunability of plasma waves assuming a gate threshold voltage of $-0.764\,$V is shown in Fig. 1. As expected, increasing the length of the channel reduces the resonant frequency.

B. SURFACE EQUIVALENCE THEOREM

With the help of the surface equivalence theorem, the fields due to a source embedded in a multilayered medium such as a transistor stack can be formulated as a set of coupled integral equations. Actual structures are replaced by a combination of equivalent electric and magnetic current sources, such that the field computation problems can be homogenized to inner and outer regions.

We consider a flat sheet for which the electric and magnetic fields in the outer region are expressed in (7) and (8), as shown at the bottom of this page, where $\mathbf{E}^i$ and $\mathbf{H}^i$ are the known incident electric and magnetic fields respectively, and k_1 is the free-space propagation constant, as shown at the bottom of the previous page. The origin and source locations are described by the position vectors, $\boldsymbol{\rho}$ and $\boldsymbol{\rho}'$ respectively. $H_0^2(\cdot)$ is the zero order Hankel function of the second kind. Similarly, fields for the interior region that only contain the scattered part are given in (9) and (10), as shown at the bottom of this page, where k_2 is the propagation constant in the interior region, as shown at the bottom of the previous page.

C. SURFACE INTEGRAL EQUATION

1) $\mathrm{TM_Z}$ POLARIZATION FOR PLASMA-WAVE EXCITATION

Next we consider a TM_z excited planar dielectric sheet lying along the x-axis and apply the surface equivalence theorem to find the electric ($\mathbf{J}_s$) and magnetic ($\mathbf{M}_s$) currents on the sheet,

$$\mathbf{J}_s = \hat{\mathbf{n}} \times \mathbf{H} = \hat{\mathbf{z}}\, \mathrm{J}(\xi), \tag{13a}$$

$$\mathbf{M}_s = -\hat{\mathbf{n}} \times \mathbf{E} = \hat{\mathbf{x}}\, \mathrm{M}(\xi) \tag{13b}$$

where the normal unit vector $\hat{\mathbf{n}}$ is in the y direction and ξ depends on x and y coordinates. We consider a plane wave propagating in the direction of the vector $\mathbf{k}$ where electric field $\mathbf{E}^i$ polarized along the z-direction is incident on the dielectric surface at an angle ϕ_i. To find the surface currents, we set up a homogeneous equivalent problem first for the region outside the dielectric sheet due to an incident field,

$$\mathbf{E}^i = \hat{\mathbf{z}}\, E_0 e^{-jk_1(x\cos\phi_i - y\sin\phi_i)} \tag{14}$$

with E_0 the amplitude of the incoming plane wave. We now express the scattered fields in terms of potentials as

$$\mathbf{E}_1^{scat} = -\frac{j\omega}{k_1^2}\left(k_1^2 + \nabla\nabla\cdot\right)\mathbf{A}, \tag{15a}$$

$$\mathbf{H}_1^{scat} = -\frac{j\omega}{k_1^2}\left(k_1^2 + \nabla\nabla\cdot\right)\mathbf{F}, \tag{15b}$$

where $\mathbf{A}$ and $\mathbf{F}$ are the magnetic and electric vector potentials respectively, given by:

$$\mathbf{A} = \frac{\mu}{4j}\int_l \mathbf{J}_s(\boldsymbol{\rho}')H_0^{(2)}(k_1|\boldsymbol{\rho}-\boldsymbol{\rho}'|)\,\mathrm{d}l', \tag{16a}$$

$$\mathbf{F} = \frac{\varepsilon}{4j}\int_l \mathbf{M}_s(\boldsymbol{\rho}')H_0^{(2)}(k_1|\boldsymbol{\rho}-\boldsymbol{\rho}'|)\,\mathrm{d}l', \tag{16b}$$

$$\mathbf{E}_1 = -\frac{\omega}{4k_1^2}\left(k_1^2 + \nabla\nabla\cdot\right)\int_C \mathbf{J}_s(\boldsymbol{\rho}')H_0^{(2)}(k_1|\boldsymbol{\rho}-\boldsymbol{\rho}'|)\,\mathrm{d}l' - \frac{1}{4\varepsilon j}\nabla\times\int_l \mathbf{M}_s(\boldsymbol{\rho}')H_0^{(2)}(k_1|\boldsymbol{\rho}-\boldsymbol{\rho}'|)\,\mathrm{d}l' + \mathbf{E}^i \tag{7}$$

$$\mathbf{H}_1 = \frac{1}{4j}\nabla\times\int_l \mathbf{J}_s(\boldsymbol{\rho}')H_0^{(2)}(k_1|\boldsymbol{\rho}-\boldsymbol{\rho}'|)\,\mathrm{d}l' - \frac{\omega}{4k_1^2}\left(k_1^2 + \nabla\nabla\cdot\right)\int_l \mathbf{M}_s(\boldsymbol{\rho}')H_0^{(2)}(k_1|\boldsymbol{\rho}-\boldsymbol{\rho}'|)\,\mathrm{d}l' + \mathbf{H}^i \tag{8}$$

$$\mathbf{E}_2 = -\frac{\omega}{4k_2^2}\left(k_2^2 + \nabla\nabla\cdot\right)\int_C \left(-\mathbf{J}_s(\boldsymbol{\rho}')\right)H_0^{(2)}(k_2|\boldsymbol{\rho}-\boldsymbol{\rho}'|)\,\mathrm{d}l' - \frac{1}{4j}\nabla\times\int_l \left(-\mathbf{M}_s(\boldsymbol{\rho}')\right)H_0^{(2)}(k_2|\boldsymbol{\rho}-\boldsymbol{\rho}'|)\,\mathrm{d}l' \tag{9}$$

$$\mathbf{H}_2 = \frac{1}{4j}\nabla\times\int_l \left(-\mathbf{J}_s(\boldsymbol{\rho}')\right)H_0^{(2)}(k_2|\boldsymbol{\rho}-\boldsymbol{\rho}'|)\,\mathrm{d}l' - \frac{\omega}{4k_2^2}\left(k_2^2 + \nabla\nabla\cdot\right)\int_l \left(-\mathbf{M}_s(\boldsymbol{\rho}')\right)H_0^{(2)}(k_2|\boldsymbol{\rho}-\boldsymbol{\rho}'|)\,\mathrm{d}l' \tag{10}$$

The electric field scattered off a flat plate oriented along the x-axis can be simply written in a scalar form due to a z-polarized incident wave and z-directed current,

$$\begin{aligned} E_1^{scat} &= -j\omega A_z \\ &= -\frac{\omega\mu}{4j}\int_l J_z(x')H_0^{(2)}(k_1|\boldsymbol{\rho}-\boldsymbol{\rho}'|)\,\mathrm{d}l' \end{aligned} \tag{17}$$

Using a similar procedure, we set up an interior equivalent with the currents reversing the signs. The total fields for the interior region only contain the scattered fields.

$$E_2^{scat} = -\frac{\omega\mu}{4j}\int_l \left(-J_z(x')\right) H_0^{(2)}(k_2|x-x'|)\,\mathrm{d}l' \tag{18a}$$

$$H_{2,x}^{scat} = -\frac{j\omega}{k_2^2}\left(k_2^2+\frac{\partial^2}{\partial x^2}\right) \int_l \left(-M_x(x')\right) H_0^{(2)}(k_2|x-x'|)\,\mathrm{d}l'. \tag{18b}$$

In order to find an equation for the electric and magnetic currents, we apply the boundary conditions at the interface ensuring the continuity of tangential component of the fields. At the interface:

$$\hat{\mathbf{n}}\times(\mathbf{E}_1-\mathbf{E}_2)=\mathbf{0} \tag{19a}$$

$$\hat{\mathbf{n}}\times(\mathbf{H}_1-\mathbf{H}_2)=\mathbf{0} \tag{19b}$$

Using (19a), (17) and (18b), we get,

$$E_i = \frac{\omega\mu}{4}\int_c J_z(x')\left[H_0^{(2)}(k_1X)+H_0^{(2)}(k_2X)\right]\mathrm{d}l'. \tag{20}$$

The computation can be simplified by expressing the second order Hankel function in terms of lower order Hankel functions using the recurrence relations [29, p. 361].

$$\frac{\mathrm{d}H_0^{(2)}(x)}{\mathrm{d}x} = -H_1^{(2)}(x)+\frac{1}{x}H_0^{(2)}(x) \tag{21a}$$

$$H_1^{(2)}(x) = \frac{x}{2}\left[H_0^{(2)}(x)+H_2^{(2)}(x)\right] \tag{21b}$$

III. NUMERICAL RESULTS

The method of moments (MoM) numerical technique provides a computational solution for the electric and magnetic currents. By using pulse basis functions with point-matching method [30], we convert the integral equations into a linear system of equations,

$$\begin{bmatrix} Z_{mn} & 0 \\ 0 & Y_{mn}\end{bmatrix}\begin{bmatrix} J_n \\ M_n\end{bmatrix} = \begin{bmatrix} E_m^i \\ H_m^i\end{bmatrix} \tag{22}$$

where Z_{mn} and Y_{mn} are the impedance and admittance terms respectively. The surface currents are obtained by multiplying the inverted impedance or admittance matrix with the incident wave vector.

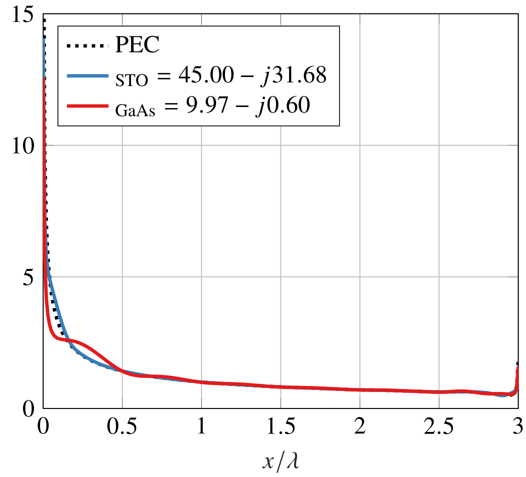

FIGURE 2. Current Distributions on a 3λ plate at edge-on incidence for PEC, strontium titanate (STO) and gallium arsenide (GaAs).

A. CURRENT DISTRIBUTION

Figure. 2 shows the absolute value of the tangential surface electric current on a TM_z polarized plate of length 3λ at edge-on ($\phi_i = \pi$) incidence. The discontinuity seen at the edge is a typical behavior commonly known as the edge condition, which characterizes the fields in the vicinity of a sharp corner. We consider sheets of gallium arsenide (GaAs) which is the most common semiconductor material used in high-frequency devices, and strontium titanate ($SrTiO_3$) which has a perovskite crystal structure and electronic properties similar to semiconductors. Both of the sheets were considered at terahertz frequencies where the material data was extracted from measurements in [24] and [31] respectively. We compared the current distribution of the two sheets with a perfect electric conductor (PEC) plate of the same length [16]. It is noted that the material having a lower dielectric constant produces a less sharp field discontinuity at the edge.

B. FAR-FIELD

The scattered electric field in the far-zone can be determined by normalizing the large argument approximation of Hankel functions, resulting in:

$$\lim_{k_1|\boldsymbol{\rho}-\boldsymbol{\rho}'|\to\infty} E_z(\boldsymbol{\rho}) \simeq \int_0^L J_z(x')e^{jk_1x'\cos(\phi_i)}\,\mathrm{d}x' \tag{23}$$

where ϕ_i is the angle of incidence. The results of our scheme are compared with other techniques that have been used in the context of thin sheets. We first assess the scattering response of a TM_z polarized dielectric sheet of permittivity $\varepsilon = 4$ having length 2.5λ and compare the results with [32], where integral equation technique was used for the first time to simulate thin structures. It uses a volume integral equation (VIE) technique, which is then collapsed to the surface of the structure. The radar cross-sections (RCS) are shown in Fig. 3. The disparity near edge-on condition is due to

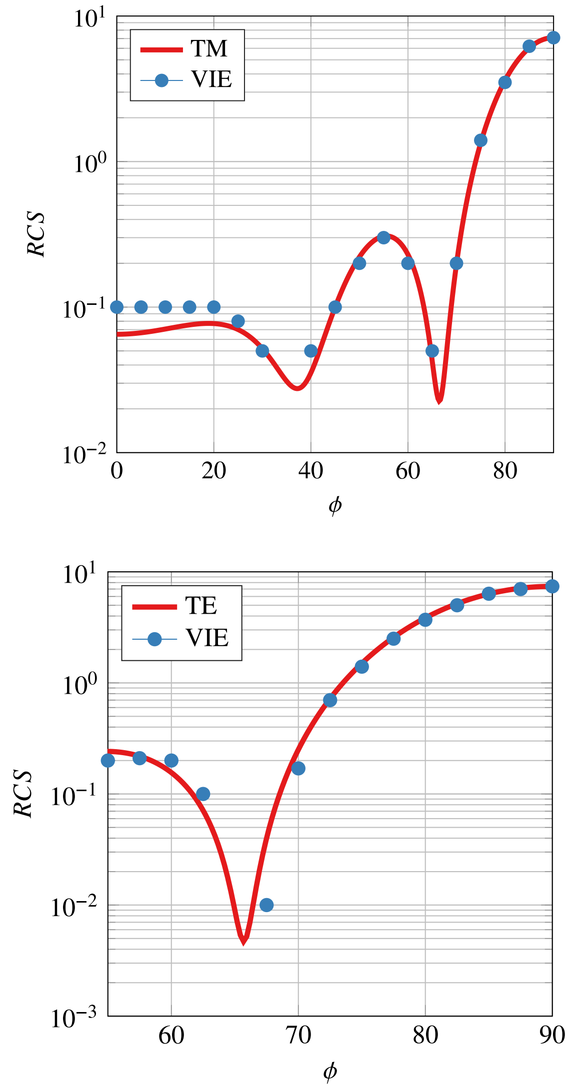

FIGURE 3. Scattering response of a 2.5λ long dielectric strip of permittivity $\epsilon = 4$, under (a) TM_z, and (b) TE_z polarization.

the fact that the structure considered in [32] had a thickness of 0.05λ, whereas in this work, we have taken an infinitesimally thin sheet. Through similar steps, the TE_z scattering expression is obtained, the results of which are shown in Fig. 3b. The difference in the scattering response observed is again attributed to the dissimilar thicknesses of the two structures.

IV. CONCLUSION

Surface integral equations for infinitesimally thin dielectric sheets were presented. The integral equation formulation, necessary to obtain the equivalent current and subsequently the scattered fields, was based on the surface equivalence theorem. The method described in this paper is well-suited for investigating the scattering properties of extremely thin structures such as two-dimensional materials, that are increasing become significant thanks to their ability to couple radiation energy into nanostructures, especially in the terahertz frequency range.

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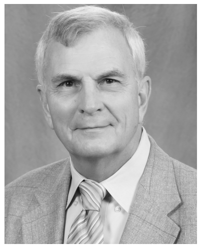

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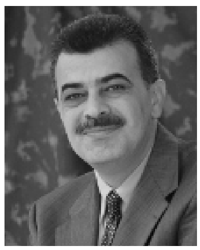

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