# Hot-electron transport in epitaxial $CoSi_2$ films

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We present a calculation of the photoelectric quantum yield of Schottky diodes, taking into account the spatial distribution of photon absorption in the metal film. We also present measurements of the quantum yield of epitaxial $CoSi_2$ diodes, with metal thicknesses varying from 25 Å up to 1000 Å. A comparison of our experimental data with the results of this model leads to the determination of the escape depth of the hot electrons in $CoSi_2$. The escape depth was found to be around 90 Å at room temperature and 100 Å at 77 K for 0.75-eV incident-photon energy and to decrease slightly with photon energy. These results are discussed and interpreted in terms of electron-phonon and electron-electron interactions.

## I. INTRODUCTION

Internal photoemission over metal-semiconductor Schottky barriers has been extensively studied over more than two decades,[1,2] and has proved to be a very valuable tool for the study of Schottky barrier properties.[3,4] Technologically, Schottky diodes can be used for infrared detection:[5] photodetectors for wavelengths as long as 12 $\mu$m have recently been fabricated.[6] From the physics perspective, the quantum efficiency of these detectors allows one to study the transport of photoexcited electrons in metals.[1] The quantum efficiency, however, results from a rather complex set of physical phenomena which are involved in the detection process, namely, (i) photon absorption in the metal film, (ii) diffusion of the photoexcited electrons towards the metal-semiconductor interface, and (iii) collection of the hot electrons in the semiconductor. This latter process, independent of film thickness, is associated with the internal quantum yield, i.e., the ratio of the number of collected electrons to the number of photoexcited electrons reaching the interface, and was discussed by Fowler[7] in the early 1930s. On the other hand, both photon absorption and hot-electron transport strongly depend on the metal film thickness. They have already been studied, but unfortunately as two independent processes. Infrared absorption has been studied in various metals such as noble metals[1] and silicides of platinum,[8] iridium,[9] and cobalt.[10] Hot-electron transport has been extensively studied both experimentally and theoretically: several observations of ballistic transport in metal films have been reported in semiconductor-metal-semiconductor structures,[11,12] while a large amount of theoretical work has been devoted to the dependence of the inelastic mean free path on the excitation energy[13,14] and to the redirection effect of quasielastic collisions (mainly electron-phonon interactions) on the escape probability.[15,2] It should be noted that most studies concerning internal photoemission poorly address the problem of the spatial distribution of photon absorption in the metal film: they either use a constant[16] or exponential[1,15] distribution profile, or do not address this point at all.[2] It has been demonstrated, however, that due to the multiple reflection of light in thin metal films, the optical reflection, transmission, and absorption coefficients are nontrivial functions of film thickness.[8-10,17] Thus a precise study of hot-electron transport in metals based on internal photoemission requires that one take into account the optical absorption distribution to calculate the quantum efficiency.

In this paper, we present a one-dimensional calculation of the quantum yield of Schottky diodes, taking into account the spatial distribution of photon absorption, i.e., of photoexcited electrons in the metal film. The yields so calculated are then compared with the measured ones obtained on epitaxial $CoSi_2$/Si Schottky diodes of different metal thicknesses. The hot-electron escape depth is then deduced and the effects of temperature and excitation energy are presented. Different relaxation mechanisms for hot electrons in $CoSi_2$, mainly electron-electron and electron-phonon scattering, are then discussed.

## II. ONE-DIMENSIONAL MODEL

A plane wave of angular frequency $\omega$ is perpendicularly incident on a thin metal film of thickness $d$, grown or deposited on a dielectric substrate, e.g., silicon in our case. The propagation of the electromagnetic wave is described in the substrate by means of a real index $n_s$ and in the metal film by a complex index $n+ik$ (with $n$ and $k$ real). $r$ and $t$ (respectively, $r'$ and $t'$) represent the Fresnel reflection and transmission coefficients of the wave on the metal-air interface (respectively metal-semiconductor interface).[17] The angles $\xi$ and $\Psi$ are defined by $r=|r|e^{i\xi}$ and $r'=|r'|e^{i\Psi}$, the wavelength in vacuum by $\lambda$, the wave vector in the metal $K$ by $\omega(n+ik)/c$, and the optical lengths respectively associated with phase rotation and attenuation of the electromagnetic wave by $L_n=\lambda/4\pi n$ and $L_k=\lambda/4\pi k$.

The Poynting vector in the metal at a distance $x$ from the metal-air interface $S(x)$ is calculated for front illumination (light incident on the metal side) taking into account the multiple reflection of the wave in the film.

 

Due to the strong absorption by the free electrons, the distance covered by the wave in the metal before extinction is small compared to the optical coherence length. The complex amplitudes of all reflected waves are thus added up in the calculation. For front illumination, $S(x)$ may be written as

$$S(x)=S_a\left|\frac{t}{1-rr'e^{2iKd}}\right|^2 \times\left[ne^{-x/L_k}-n|r'|^2e^{(x-2d)/L_k}+2k|r'|e^{-d/L_k}\sin\left[\frac{d-x}{L_n}+\Psi\right]\right], \quad (1)$$

where $S_a$ is the Poynting vector in air of the incident wave; the prefactor describes the effect of multiple reflections of the wave in the metal film, the first term in parentheses describes the energy flux propagating in the incident direction, i.e., from the air to the semiconductor, the second, the energy flux propagating in the reverse direction, and the last, the interferences between waves propagating in opposite directions.

The number $N(x)dx$ of photons absorbed in the region between $x$ and $x+dx$, which is equal to the number of photoexcited electrons in the same region, is given by

$$N(x)dx=-\frac{1}{h\nu}\frac{\partial S(x)}{\partial x}dx \ . \quad (2)$$

We must then take into account the effect of collisions on the electron escape over the Schottky barrier. The escape probability is the probability of the hot electron maintaining an energy higher than the barrier energy until it reaches the interface. We suppose that this escape probability can be described by an inelastic escape depth $L$, i.e., as an exponentially decreasing function of the distance between the position of the hot-electron creation and the barrier. Since the typical energy of an excited electron is much less than the metal work function, we assume a total reflection of the hot electron on the metal-air interface and therefore a unity reflection coefficient. Taking into account both directions of electron diffusion, i.e., toward both interfaces, the probability $p(x)$ of an electron excited at $x$ reaching the metal-semiconductor interface is then

$$p(x)=\tfrac{1}{2}e^{-d/L}(e^{x/L}+e^{-x/L}) \ . \quad (3)$$

In order to derive the internal quantum yield $Y_I$, i.e., the probability of an excited electron at the interface escaping in the semiconductor, the conservation of the component of the electron wave vector parallel to the interface is assumed during the transition.[7] $Y_I$ is then equal to the probability of an excited electron having a kinetic energy in the direction perpendicular to the interface higher than the barrier height $\varphi$; assuming $h\nu \ll E_F$, it is given in the free electron model by[18]

$$Y_I=\frac{(h\nu-\varphi)^2}{4E_Fh\nu} \ . \quad (4)$$

Finally, the external quantum yield $Y_E$, equal to the probability of an incident photon giving rise to a collected electron, is

$$Y_E=\int_0^d Y_Ip(x)\frac{N(x)}{N_i}dx \ , \quad (5)$$

where $N_i$ is the number of incident photons, equal to $S_a/h\nu$. We then obtain

$$Y_E=Y_I\left|\frac{t}{1-rr'e^{2iKd}}\right|^2 Le^{-pd} \times\left[\frac{n}{L_K^2-L^2}[L_K(1+|r'|^2)\sinh(d/L)+L(1-|r'|^2)\cosh(d/L)-L(e^{d/L_K}-|r'|^2e^{-d/L_K})] +\frac{2k|r'|}{L^2+L_n^2}[L_n\cos\Psi\sinh(d/L)-L\sin\Psi\cosh(d/L)+L\sin(d/L_n+\Psi)]\right], \quad (6)$$

where $p=1/L+1/L_k$.

Our calculation can be checked against the Heavens formulation[17] of absorption of electromagnetic energy in a metal film: if the escape depth $L$ is infinite, every electron excited with an energy higher than the barrier will eventually be collected and the external quantum yield is then reduced to the absorption coefficient times the internal quantum yield. It can easily be verified that the external quantum yield, calculated from expression (6) in the limit of infinite escape depth and unity internal quantum yield, is indeed exactly equal to the absorption coefficient calculated using the Heavens formulas. It should also be noted that the absorption first increases with film thickness, reaches a maximum, and then decreases towards its limiting value. The existence of this maximum, which has been observed experimentally,[8,9] is a direct consequence of interference effects in the metal film and justifies the apparent complexity of our model.

We can then calculate the external yield for finite values of the escape depth $L$ and incident light in the

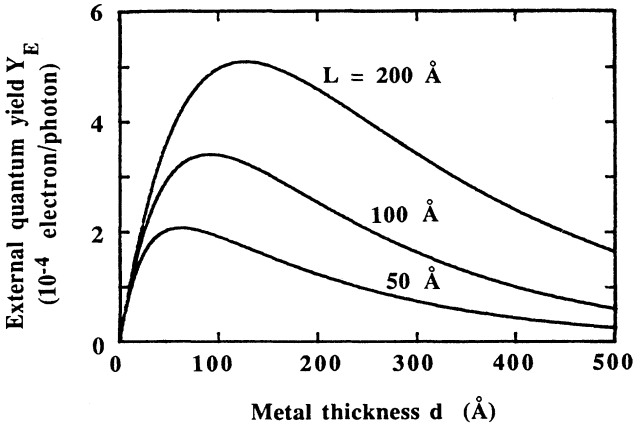


FIG. 1. Front illumination external quantum yield $Y_E$ of Schottky diodes calculated as a function of metal thickness $d$. The photon energy is 1 eV, the Fermi energy $E_F$ is taken as equal to 3.5 eV, the Schottky barrier height $\varphi$ is 0.64 eV, the metal indices are $n=1$ and $k=5.4$, and the calculation has been carried out for three values of escape depth $L$, 50, 100, and 200 Å.

near infrared, i.e., with $h\nu$ between 0.75 and 1 eV. In this energy range, the silicon index $n_s$ is 3.3 while the complex index of $CoSi_2$ has been measured in a previous study.[10] Figure 1 shows the dependence of the calculated external quantum yield on metal thickness for a photon energy equal to 1 eV and different values of the escape depth: 50, 100, and 200 Å. The important feature of this figure is that the quantum yield exhibits a sharp maximum for a metal thickness of the order of the escape depth $L$; the decrease in yield with metal thickness is much more pronounced in this case than with an infinite $L$. This arises because electrons excited far from the barrier are, for a finite value of $L$, thermalized before being collected. Finally, it should be added that the slope of the quantum yield plotted in logarithmic scale for large film thicknesses is the larger of $L$ and $L_k$.

## III. EXPERIMENT

The $CoSi_2$ films were grown in our laboratory on 2-in. $\langle 111 \rangle$ $n$-type degenerate Si wafers (in order to minimize series resistances) with a 1.5–2-$\mu$m-thick epitaxial buffer layer (doped to $3\times10^{15}$ $cm^{-3}$) on top. After a standard cleaning procedure, the films were grown by ultrahigh-vacuum deposition of Co (base pressure in the few $10^{-10}$ Torr) at room temperature and followed by a solid phase reaction at 650 °C. All these films were extensively studied using electron and x-ray diffraction, Rutherford backscattering, and transmission electron microscopy, and shown to be epitaxial.[4,12] The diodes were then fabricated by standard lithographic and chemical etching techniques, with diameters varying between 0.25 and 1.5 mm and then mounted in a nitrogen cryostat.

The internal photoemission setup has been described elsewhere.[4] The incident chopped beam was delivered by a double prism monochromator and separated using a beam splitter. One part of the beam was focused onto the diodes (front illumination) while the other was sent to a pyroelectric photodetector allowing determination of the incident photon flux at each photon energy (with a numerical factor which depends only on the ratio of the respective area of the diode and the photodetector, and on the transmission and reflection coefficients of the beam splitter). The photovoltage was measured using a lock-in amplifier either directly on the diode or on a load resistance. In the former case, the photocurrent is equal to the photovoltage divided by the diode internal resistance, which was measured precisely at the chopping frequency using an ac voltage generator. The measuring frequency was around 100 Hz and the typical internal resistance was of the order of 10 k$\Omega$ at 300 K. The measured photovoltage was typically in the 100-$\mu$V range, yielding a photocurrent in the 10-nA range. The latter method was used at low temperature as the diode internal resistance could thus be orders of magnitude larger and could no longer be measured accurately. A parallel resistance of about 10 k$\Omega$ was then connected, allowing the charge impedance to remain perfectly known and thus to deduce the exact value of the photocurrent from the photovoltage measurement. The measurements were carried out on diodes with $CoSi_2$ thicknesses ranging between 25 and 1000 Å at temperatures of between 300 and 77 K and photon energies of between 0.5 and 1 eV. The photocurrent dependence on the incident photon energy was consistent with the Fowler theory,[7,18] in excellent agreement with expression (4) of the internal quantum yield. Figure 2(a) [respectively, 2(b)] shows the photocurrent per photon (external quantum yield) as a function of metal thickness measured at 300 K (respectively, 77 K) for three photon energies, 0.90, 0.95, and 1 eV. The yield increases with metal thickness, reaches a sharp maximum at 75 Å, and then decreases abruptly. The shape of the $Y_E(d)$ curves resembles that of the calculated ones, with, however, a measured photocurrent which is slightly smaller for the 100- and 200-Å-thick films than the calculated one; this leads to a sharper maximum in the experimental curve than in the theoretical one. As previously mentioned, the curves related to different photon energies are proportional to each other by a factor equal to the ratio of the internal quantum yields. Furthermore, the 77-K photocurrents are slightly larger than the 300-K ones, in spite of a 40-meV increase in the Schottky-barrier height,[4] thus indicating that the escape depth is larger at 77 K than at room temperature. Since the maximum yield occurs for a metal thickness of 75 Å, our calculation indicates that the escape depth $L$ of electrons in $CoSi_2$ lies around this value. A more precise value can be deduced by a direct comparison of the results with the theoretical curves, based on the position of the maximum yield and on the shape of the curve for thicknesses between 75 and 400 Å. For 1000-Å-thick films, the yield is indeed dominated by the optical attenuation length $L_k$ [which is of the order of 180 Å (Ref. 10)] and shows little dependence on $L$. Figure 3 shows the variation in $L$ with photon energy as deduced from our measurements at 300 and 77 K. $L$ decreases slightly with photon energy and is indeed larger at 77 than at 300 K. We would also like to mention that the temperature dependence of the photo-

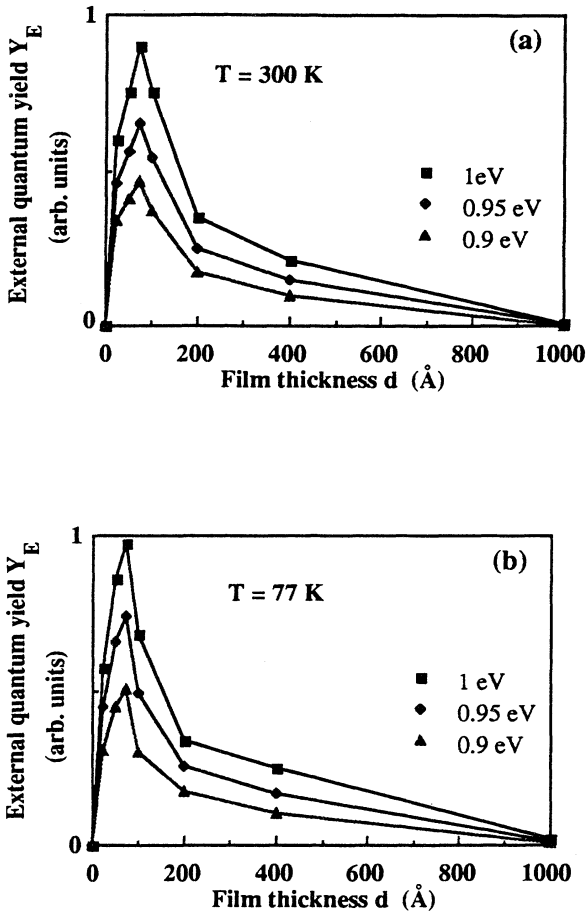


FIG. 2. Experimental external quantum yield or photocurrent per incident photon measured in $CoSi_2$ Schottky diodes at 300 K (a) and at 77 K (b) as a function of metal thickness $d$. The results are presented for three different photon energies: 1, 0.95, and 0.9 eV. The photocurrent is given here in arbitrary units, with the same numerical factor for both (a) and (b), so that the photocurrent values of both figures can be compared.

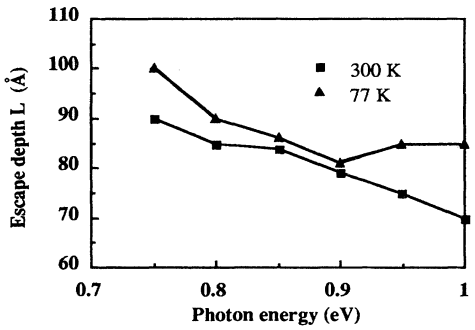


FIG. 3. Hot-electron escape depth $L$ in $CoSi_2$ deduced from photocurrent measurements in Schottky diodes as a function of photon energy. The results are given in 300 and 77 K, with an accuracy of the order of 20 Å.

current on a given diode indicates a slightly larger ratio $L(77\text{ K})/L(300\text{ K})$ than the one obtained from the calculation, indicating that the 77-K mean free path is actually slightly larger than indicated in Fig. 3.

## IV. DISCUSSION

Electrons in metals with energies much more than $kT$ above the Fermi level are usually referred to as hot electrons. However, it should be pointed out that the metal here cannot be considered to contain a hot-electron gas as only a very limited number of electrons are excited while others are still in equilibrium with the lattice.[19] As a consequence, interactions between hot electrons are negligible. Statistical averaging of the hot-electron parameters (velocity and energy) is replaced here by a time averaging, the equivalence between these two ways of averaging arising from ergodicity. The excess energy of a hot electron in a metal is less than the photon energy as its initial energy is equal to or lower than $E_F$.[20] It varies, however, in the same way as the photon energy and we will therefore discuss our results using indifferently the photon energy and electron excess energy. Our model does not take into account elastic collisions and momentum redistribution. Again, we will discuss our results mainly in terms of energy relaxation. Since the velocity of a hot electron is isotropic before and after an elastic collision, the momentum relaxation is less important than the energy relaxation in determining the hot-electron escape probability. From these preliminary considerations, we will summarize our results in the following way.

(i) The escape depth $L$ of hot electrons (0.7–1 eV) in $CoSi_2$ is around 80 Å.

(ii) $L$ increases slightly with decreasing temperature.

(iii) $L$ tends to decrease with the electron excess energy.

Different mechanisms may contribute to the relaxation of the hot-electron energy, involving acoustic or optical phonons, and cold electrons. Collisions with defects, being essentially elastic,[21] do not contribute to the electron energy relaxation. First, we shall consider collisions with acoustic phonons. Although some relatively high-energy phonons (10 meV) can be emitted, the average energy transferred during a collision with an acoustic phonon remains small compared to the electron energy. Their role in the electron energy relaxation is thus neglected here.[21,22] However, even if they do not contribute in the decrease of the inelastic mean free path, they may decrease the electron escape probability as well as the escape depth by increasing the distance traveled by the electron before the escape. This effect should occur mainly in thick films (thickness larger than the inelastic mean free path) while in thin films Dalal[2] and Vickers[16] both claim that the yield is enhanced through the redistribution of momentum by elastic phonon scattering. These effects may be temperature dependent as some thermally excited acoustic phonons with a small wave vector may be absorbed. Indeed, calculations[23] in Si show that the momentum relaxation time for very-high-energy electrons has a more pronounced temperature dependence than has the energy relaxation time. The importance of elastic scattering by acoustic phonons could

also explain the large decrease in transmission factor with temperature observed in semiconductor-metal-semiconductor structure.[12] In this case, the hot-electron initial distribution is indeed highly anisotropic and the momentum relaxation greatly reduces the transmission factor of the metal film.

Secondly, we will consider the effect of optical phonons which may contribute significantly to the energy relaxation. Their energy being equal to or higher than $kT$, optical phonons are mainly emitted by hot electrons and, therefore, their contribution is only slightly dependent on the lattice temperature. In semiconductors, the optical-phonon contribution determines the saturation velocity, which decreases slightly with temperature.[21,24] The energy relaxation time in Si due to optical-phonon–electron collisions is therefore expected to decrease only slightly with temperature.[23] The weak temperature dependence of the escape depth may thus be caused either by the latter effect or by the more indirect effect of the acoustic phonons on the electron trajectories.

Let us now consider the dependence of the phonon scattering on the hot-electron energy. The collision rate is proportional to the square of the interaction potential and to statistical occupation factors of the initial and the final states which respect the total energy and momentum conservations. Since the initial electron excess energy is much higher than the optical-phonon energies, the statistical factors should not be very dependent on the electron energy. The interaction potential that must be used here is a screened Coulombic potential; its Fourier transform is proportional to $(k_0^2+q^2)^{-1}$ where $k_0$ is the inverse of the screening length and $q$ is the electron momentum change.[21,22] Assuming a parabolic band structure, and after averaging over the scattering angle, this term is proportional to $(\hbar^2 k_0^2/2m+2E)^{-1}$ and therefore decreases with the electron kinetic energy $E$. This decrease can be important in a semiconductor because the Debye screening length is large compared to interatomic distances and because the relative kinetic energy variations may be large. This effect is indeed responsible for the so-called polar runaway effect.[21,25] In a metal, however, the Thomas-Fermi screening length is much smaller and the variation in the electron kinetic energy is small compared to the total one; consequently, the interaction potential dependence on electron excess energy is expected to be weak. Experimentally, it has been found in a polar semiconductor (GaAs) that the inelastic mean free path increases from 1000 Å at 0.1 eV to 1500 Å at 0.3 eV.[26] Simulations in Si (Ref. 23) also reveal a very slight increase in the energy relaxation time for energies from 0.1 to 1 eV. In a metal, we thus assumed that the energy relaxation time is only slightly dependent on the electron energy. It is prime importance at this point to focus on the difference between the energy relaxation time $\tau_{ph}$ and the average total time $T_{ph}$ required by an electron to be thermalized by phonon emission to an energy below the Schottky barrier height, i.e., to be lost for internal photoemission. Taking the photon energy as the electron excess energy, then $T_{ph}$ equals $\tau_{ph}(h\nu-\varphi)/\hbar\Omega_{op}$ where $\hbar\Omega_{op}$ is the energy of optical phonons and $\tau_{ph}$ is assumed to be independent of $h\nu$. This means that electrons with higher energies have a larger escape probability. Because of the momentum redistribution, the corresponding mean free path does not vary linearly with $T_{ph}$ (the diffusion limit would be a square root dependence) but is an increasing function of the electron excess energy.

The third point will be devoted to the electron-electron interactions. The mean free path for electron-electron collisions can be estimated[27] by $1/N\sigma S$ where $N$ is the carriers density, $\sigma$ the electron-electron cross section, and $S$ the statistical occupation factor. As previously explained, the interaction potential and $\sigma$ are not supposed to be strongly dependent on the excitation energy. $\sigma$ has been calculated for sodium[27] and was found to be in the $10^{-15}$-$cm^2$ range. As pointed out by Bardeen and Pines,[28] this value is rather large but, for thermally excited electrons, where $S$ equals $(kT/E_F)^2$, the possible scatterings are so greatly restricted by Pauli's exclusion principle[14] that collisions are infrequent. On the contrary, for optically excited electrons, $S$ equals[14] $[(E-E_F)/E_F]^2$, (or in very thin films varies as $[(E-E_F)/E_F]^2/\ln(E-E_F)$ to account for two-dimensional (2D) effects[29,30]), and electron-electron collisions become more frequent. Yet, these collisions are rather infrequent in semiconductors due to their low electronic densities. When the carrier density is increased, however, they are expected to play a more important role[31–33] and are likely to be predominant in metals ($CoSi_2$ carrier density is $3\times10^{22}$ $cm^{-3}$). Again, the total time $T_{ee}$ required by an electron to relax to an energy below the barrier height is equal to the sum of all the electron-electron relaxation times $\tau_{ee}(E)$, where the sum is extended over all intermediate states. Both $\tau_{ee}(E)$ and the average energy $dE$ exchanged during the collision strongly depend on $E$ and the sum cannot be easily calculated. It has been estimated[13] that $dE$ is an important part of the excess energy $E$ (e.g., two-thirds in aluminum). In this case $T_{ee}$ should be close to $\tau_{ee}(h\nu)$, and the escape probability and corresponding mean free path are decreasing functions of the excess energy. As a result, the slight decrease in the escape depth with increasing electron excess energy already observed could possibly be an indication of the importance of the electron-electron interactions in the relaxation of photoexcited electrons in $CoSi_2$.

We would like to compare the absolute value of the escape depth measured in $CoSi_2$ with values found in other metals and semiconductors. Crowell and co-workers found escape depths in noble metals in the 100–200-Å range. Relaxation times of optically excited electrons in the $10^{-14}$-s range have been reported in metals;[34] we found[10] a relaxation time of $2.5\times10^{-15}$ s in $CoSi_2$, which is consistent with the relatively short mean free path presented in this work. In III-V compound semiconductors, Eastman[26] measured values of an inelastic mean free path between collisions with optical phonons of around 1000 Å for electron energies higher than the optical phonon energy. Energy relaxation times of the order of $5\times10^{-13}$ s to $10^{-12}$ s are reported in Si and GaAs (Refs. 23 and 21) for electron energies of around 1 eV. These relaxation times correspond to the time between two col-

lisions, and the time required to thermalize an electron by 300 or 400 meV would be even longer. The comparison between energy relaxation times in metals and in semiconductors together with the comparison of their electron densities is thus particularly striking. For all of the above reasons, we believe that the inelastic escape depth deduced from our measurements in $CoSi_2$ is, at least partially, related to electron-electron interactions. In addition, it should be noted that the 2D plasma energy is lower than the 3D one: the long-range electron-electron interactions might therefore also be considered as much as the short-range ones.

Finally, we compare the relative magnitude of both the experimental and theoretical quantum yields of Schottky diodes. The measurements were performed on a diode with a $CoSi_2$ thickness of 75 Å. We measured the photocurrent and photon flux directly by permuting the diode and the photodetector. We front illuminated them through a small (0.5 mm diameter) hole in order to ensure the equality of the optical power received by the diode and the detector (whose diameters are slightly different and of the order of 1 mm). At a photon energy of 1 eV and 300 K a photocurrent of 6.6 nA was measured for an optical power of 5.2 $\mu$W, thus leading to an external quantum yield of $1.3\times10^{-3}$. Our model, for the same thickness, gave an escape depth $L$ of 70 Å and, with the same parameters as those used in Fig. 1, an external quantum yield of $2.6\times10^{-4}$. We believe that the discrepancy between the predicted and observed yields arises from the expression of the internal quantum yield used. While the quadratic dependence of the yield on $h\nu-\varphi$ is beyond doubt, the actual prefactor is still a subject of controversy. Even with an infinite escape depth, the total absorption coefficient in a 75-Å-thick film being around 0.1, the calculated yield would be $5\times10^{-4}$ for $h\nu$ equal to 1 eV. Furthermore, external yields of a few percent have been reported in PtSi/Si diodes[5] and seem to be in contradiction to the very small internal yield calculated from formula (4). Thus, on the one hand, the actual internal yield is suspected of being higher than that used in our calculation. On the other hand, the yield in such a thin film (75 Å) could be enhanced by a momentum redistribution effect.

## V. CONCLUSION

We have presented a calculation of the external quantum yield of Schottky diodes based on the local dependence of the optical absorption. An escape depth is assumed for the hot electrons while the quasielastic collisions and the wave-vector redistributions are neglected. We performed measurements of the photocurrent per incident photon in $CoSi_2$ $n$-type Si diodes at temperatures between 300 and 77 K, with a metal thickness ranging from 25 to 1000 Å. The good agreement between the theoretical and the observed dependence of the external yield on metal thickness led to determination of the hot-electron escape depth in $CoSi_2$. It was found to be 90 Å at 300 K and 100 Å at 77 K for 0.75-eV incident photons, and to decrease slightly with photon energy. These results are interpreted in terms of electron-phonon and electron-electron collisions. The dependence of the escape depth on photon energy and comparison with the inelastic mean free path of hot electrons in semiconductors seem to indicate that electron-electron collisions play an important role in hot-electron energy relaxation in $CoSi_2$.

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[1]C. R. Crowell, W. G. Spitzer, L. E. Howarth, and E. E. LaBate, Phys. Rev. **127**, 2006 (1962).
[2]V. L. Dalal, J. Appl. Phys. **42**, 2274 (1971).
[3]S. M. Sze, C. R. Crowell, and D. Khang, J. Appl. Phys. **35**, 2534 (1964).
[4]J. Y. Duboz, P. A. Badoz, F. Arnaud d'Avitaya, and E. Rosencher, Phys. Rev. B **40**, 10 607 (1989).
[5]W. F. Kosonocky, F. V. Shallcross, T. S. Villani, and J. V. Groppe, IEEE Trans. Electron Devices **ED32**, 1564 (1985).
[6]B.-Y. Tsaur, C. K. Chen, and B. A. Nechay, IEEE Electron Device Lett. **11**, 415 (1990).
[7]R. H. Fowler, Phys. Rev. **38**, 45 (1931).
[8]J. M. Mooney, J. Appl. Phys. **64**, 4664 (1988).
[9]C. K. Chen, B.-Y. Tsaur, and M. C. Finn, Appl. Phys. Lett. **54**, 310 (1989).
[10]J. Y. Duboz, P. A. Badoz, J. Henz, and H. von Känel, J. Appl. Phys. **68**, 2346 (1990).
[11]C. R. Crowell and S. M. Sze, Phys. Rev. Lett. **15**, 659 (1965).
[12]E. Rosencher, P. A. Badoz, J. C. Pfister, F. Arnaud d'Avitaya, G. Vincent, and S. Delage, Appl. Phys. Lett. **49**, 271 (1986).
[13]J. J. Quinn, Phys. Rev. **126**, 1453 (1962).
[14]J. J. Quinn and R. A. Ferrel, Phys. Rev. **112**, 812 (1958).
[15]E. O. Kane, Phys. Rev. **147**, 335 (1966).
[16]V. E. Vickers, Appl. Opt. **10**, 2190 (1971).
[17]O. S. Heavens, *Optical Properties of Thin Solid Films* (Butterworths, London, 1955), Chap. 4.
[18]J. M. Mooney and J. Silverman, IEEE Trans. Electron Devices **32**, 33 (1985). The factor of 4 in the denominator of $Y_I$ (instead of the usual 8) arises from the fact that we have already taken into account both possible directions of electron wave vector in the expression (3) of the probability of an electron reaching the metal-semiconductor interface.
[19]The typical photon flux incident on a 1-mm-diameter diode is about $10^{14}$/s; the relaxation time of an electron being of the

order of $10^{-15}$ s, a photoexcited electron has, on average, enough time to relax its energy before the next photoelectron is created (Ref. 12).

[20]When the internal photoemission yield [relation (4)] is calculated, the optical transition probability is assumed to be the same for all electrons between $E_F$ and $E_F - h\nu$. If we assume that the electron excess energy equals the photon energy, i.e., that only electrons at the Fermi level are excited, then the yield would depend linearly on $h\nu - \varphi$. Since this latter dependence is not experimentally observed, this shows that the electron excess energy indeed differs from the photon energy.

[21]L. Reggiani, *Hot Electron Transport in Semiconductors* (Springer-Verlag, Berlin, 1985), Vol. 58, Chaps. 2 and 8.

[22]N. Ashcroft and N. Mermin, *Solid State Physics* (CBS, Philadelphia, 1976), Chap. 26.

[23]E. Rosencher, J. Phys. (Paris) Colloq. **42**, C7-351 (1981).

[24]S. M. Sze, *Physics of Semiconductor Devices,* 2nd ed. (Wiley, New York, 1981).

[25]I. B. Levinson, Fiz. Tverd. Tela (Leningrad) **7**, 1362 (1965) [Sov. Phys.—Solid State **7**, 1098 (1965)].

[26]L. F. Eastman, J. Phys. (Paris) Colloq. **42**, C7-263 (1981).

[27]E. Abrahams, Phys. Rev. **95**, 839 (1954).

[28]J. Bardeen and D. Pines, Phys. Rev. **99**, 1140 (1955).

[29]G. F. Giuliani and J. J. Quinn, Phys. Rev. B **26**, 4421 (1982).

[30]A. V. Chaplik, Zh. Eksp. Teor. Fiz. **60**, 1845 (1971) [Sov. Phys.—JETP **33**, 997 (1971)].

[31]R. Straton, Proc. R. Soc. London, Ser. A **246**, 406 (1958).

[32]A. Ghosal, D. Chattopadhyay, and N. N. Purkait, Appl. Phys. Lett. **44**, 773 (1984).

[33]M. Heiblum, *High Speed Electronics* (Springer-Verlag, Berlin, 1986), pp. 11–18.

[34]F. Abelès, *Optical Properties of Solids* (North-Holland, Amsterdam, 1972), Chap. 3.