PHYSICAL REVIEW B VOLUME 57, NUMBER 3 15 JANUARY 1998-I

# $Al_{0.15}Ga_{0.85}N$/GaN heterostructures: Effective mass and scattering times

S. Elhamri, R. S. Newrock, and D. B. Mast
*Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221-0011*

M. Ahoujja and W. C. Mitchel
*Wright Laboratory, WL/MLPO, W-PAFB, Ohio 45433-7707*

J. M. Redwing, M. A. Tischler, and J. S. Flynn
*Advanced Technology Materials, Inc., 7 Commerce Drive, Danbury, Connecticut 06810*

(Received 14 April 1997; revised manuscript received 21 July 1997)

We have observed well-resolved Shubnikov–de Haas oscillations in the two-dimensional electron gas in $Al_xGa_{1-x}N$/GaN heterojunctions, and determined the GaN electron effective mass ($m^*$) and the quantum scattering time ($\tau_q$). We found $m^*=0.18m_0\pm0.02m_0$ in agreement with theoretical calculations, but slightly smaller than the values previously reported from optical experiments. The value of $\tau_q$ was found to be $0.13\times10^{-12}$ sec, which is about a factor of 6 smaller than the classical scattering time ($\tau_c=0.77\times10^{-12}$ sec). This difference between $\tau_q$ and $\tau_c$ is attributed to a significant amount of small angle scattering, most likely due to charged defects at the epilayer/substrate interface. [S0163-1829(97)01947-4]

The III-V-nitride-based semiconductors are presently attracting considerable interest because of their potential for use in blue and ultraviolet optoelectronics and for high-temperature/high-power/high-frequency electronic device applications.[1,2] While gallium nitride (GaN) and other III nitrides have been studied since the 1960's,[1] the recent demonstrations of a blue-light-emitting diode[3] and laser,[4] and microwave field effect transistors[5,6] have excited increased interest. While similar in many ways to the more common III-V semiconductors such as GaAs and InP, the nitrides have several significant differences. They crystallize in one of two polytypes, a wurtzite type (hexagonal) and a zinc-blende type (cubic) with the wurtzite type being the most common. Unlike the InAs-GaAs-AlAs system, wurtzite InN-GaN-AlN alloys have direct band gaps over the whole alloy range, from the 1.9-eV band gap of InN through the 3.4-eV gap of GaN to 6.2 eV for pure AlN.[1,2] It is this wide range of band gaps, covering nearly the whole visible spectrum and the ultraviolet, that makes them so attractive for light-emitting diodes and lasers, while the high breakdown field (200 V) and saturated drift velocity ($2.7\times10^7$ cm/s) (Ref. 7) are responsible for the interest in high-power and high-frequency devices.

Although much work has been devoted to GaN and the other nitride-based semiconductors since the early 1970's, many of their important properties are still not well defined compared to the more commonly studied semiconductors such as Si and GaAs. In particular, the early reported values for the electron effective mass varied from $0.19m_0$ to $0.27m_0$ (Refs. 8–10) with the value of $0.2m_0$ reported by Barker and Ilegems[9] being the most widely referenced value. Recent reports of optical measurements of $m^*$ are centering about the value of $0.22m_0$. Drechsler *et al.*,[11] studying epitaxial GaN on sapphire, used cyclotron resonance (CR) to obtain a value of $m^*=0.20\pm0.005m_0$. Wang *et al.*,[12] also using CR, measured a value of $0.023m_0$ for the electron effective mass in the two-dimensional electron gas (2DEG) formed at an $Al_xGa_{1-x}N$/GaN heterojunction, and Perlin *et al.*[13] used infrared reflectivity measurements of bulk crystals of GaN to determine a value of $0.22\pm0.02m_0$, respectively. However, the two most recent calculations[14,15] of $m^*$give values slightly below $0.2m_0$. While small, the difference between theory and experiment appears significant and deserves further investigation. In addition, there are very few reports on the measurement of the scattering time.

The Shubnikov–de Haas (SdH) effect, quantum oscillations in the magnetoresistance, has long been an effective tool for the measurement of the properties of electrons in semiconductors and in 2DEG's in general. It has been used to determine both $m^*$ and $\tau_q$in a variety of materials. However, in the only previous report of SdH and quantum Hall effects in $Al_xGa_{1-x}N$/GaN (Ref. 16) the oscillations were visible only at fields above 10 T and were too poorly resolved to analyze. We report here the first well-resolved SdH oscillations in this material and the analysis of the data to determine both $m^*$ and $\tau_q$. Earlier, we reported preliminary measurements of the electrical properties of this sample, including the highest reported low-temperature mobility for a GaN 2DEG.[17] These experiments are the first electrical measurement of $m^*$ in GaN. The value determined, $(0.18\pm0.02)$ $m_0$, is lower than the recent CR measurements[12,13] but in close agreement with the recent theoretical calculations.[14,15] We attribute the small difference between the results reported here and the other measurement of $m^*$ in a GaN 2DEG by Wang *et al.*[12] to differences in the samples due to the silicon carbide and sapphire substrates used in the two experiments. Our measurement of $\tau_q$ is the first in GaN and we find that the ratio $\tau_c/\tau_q=5.92$, indicating a high percentage of small-angle scattering, as will be discussed later.

The standard treatment of the SdH effect in 2DEG systems is given in the review by Ando, Fowler, and Stern[18] and in a paper by Coleridge and co-workers.[19] For the case where the carrier density of the 2DEG is low enough so that only one electric subband is occupied, the oscillating portion of the magnetoresistance can be expressed as[19]

$$\frac{1}{2}\frac{\Delta\rho_{xx}}{\rho_0}=2\frac{\chi}{\sinh(\chi)}\exp\left(\frac{-\pi}{\omega_c\tau_q}\right)\cos\left(\frac{2\pi\epsilon}{\hbar\omega_c}-\pi\right), \qquad (1)$$

where $\rho_0$ is the zero field resistivity, $\omega_c=eB/m^*$ is the cyclotron frequency, $\chi$ is equal to $2\pi^2k_BT/\hbar\omega_c$, and $\epsilon$, the energy difference between the Fermi level and the minimum of the first electric subband $E_1$ is given by $\epsilon=E_F-E_1=\pi\hbar^2n/m^*$, where $n$ is the carrier density of the 2DEG occupying the first electric subband. In the case of our samples, only the first electric subband is occupied.

The effective mass of the 2DEG can be determined from the temperature dependence of the SdH oscillation amplitude at a fixed magnetic field. If we approximate sinh($\chi$) by exp($\chi$)/2, we can express the amplitude $A$ of the SdH oscillation at a given magnetic field as

$$\ln\left(\frac{A}{T}\right)\approx C-\frac{2\pi^2k_Bm^*}{e\hbar B}T, \qquad (2)$$

where C is a temperature-independent term. A plot of ln($A/T$) versus $T$ yields a straight line with a slope of $(-2\pi^2k_Bm^*/e\hbar B)$ from which $m^*$ can be evaluated.

The quantum scattering time, also called the single-particle lifetime $\tau_q$ differs from the more commonly used transport lifetime, or the classical scattering time $\tau_c$ in that the former includes all scattering events while the latter is dominated by large-angle scattering events.[20,21] The classical scattering time is determined from low-field Hall measurements $\mu=e\tau_c/m^*$. The quantum scattering time is a measure of the collision broadening of the Landau levels and is related to the half-width of the broadened Landau level through $\Gamma=h/2\tau_q$(Ref. 20) and can be obtained from the amplitude of the SdH oscillations at a given temperature using a ‘‘Dingle plot.’’[19] If at a fixed temperature $T$ we use our data to evaluate the amplitude of the oscillations and the magnitude of the quantity $(\Delta R/4R_0)/[X/\sinh(X)]$ (where $R_0$ is the zero field resistance), we can evaluate the quantum scattering time from the slope of the straight line described by[19,22,23]

$$\ln\left(\frac{1}{4}\frac{\Delta R}{R_0}\frac{\sinh(X)}{X}\right)=C-\left(\frac{\pi m^*}{e\tau_q}\right)\frac{1}{B}, \qquad (3)$$

The samples used for this study are single $Al_{0.15}Ga_{0.85}N$/GaN heterostructures grown on either SiC or sapphire substrates. The structure of the SiC sample is shown in the inset of Fig. 1; the sapphire substrate samples were similar. (More details on the sample grown are given in Ref. 17, where the low-field mobility and the carrier concentration versus temperature data are given.) The samples were slowly cooled to 0.7 K in a $^3$He cryostat equipped with a 9-T superconducting magnet. The temperature was then varied between 0.7 and 15 K, and at each temperature the longitudinal resistance $R_{xx}$ was measured as a function of $B$.

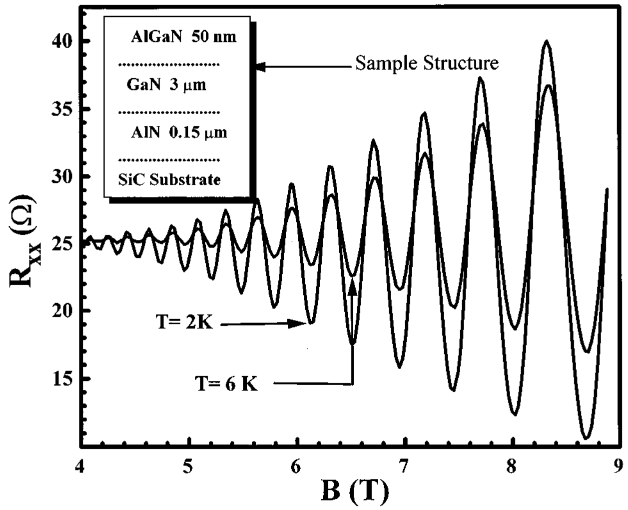

FIG. 1. $R_{xx}$ as a function of $B$ for two temperatures. The inset shows the sample structure for the sample with the SiC substrate.

Figure 1 shows $R_{xx}$ as a function of $B$ for two of these temperatures for the sample grown on the SiC substrate. The 20-K carrier concentration and mobility of this sample, as measured by low-field Hall effect, were $6.4\times10^{12}$ cm$^{-2}$ and 7480 cm$^2$/Vs, respectively. These are a relatively high concentration and low mobility for SdH experiments, but the oscillations are very well resolved. We also investigated similar samples grown on sapphire substrates in the same reactor. These samples had lower- but similar-magnitude low-temperature mobilities and similar carrier concentrations. The best of these samples had a 20-K carrier concentration of $8.7\times10^{12}$ cm$^{-2}$ and mobility of 5730 cm$^2$/V s, which are not significantly different from the SiC substrate sample. However, we were not able to detect any indication of oscillations in any of these samples up to 9 T at 0.7 K. We note that in Fig. 1 the positions of the extrema of $R_{xx}$ are the same for both temperatures, indicating that the carrier concentration is fixed over this temperature range. The absence of *significant* parallel conduction in this type of structure is confirmed by comparing the Hall and SdH carrier densities ($6\times10^{12}$ and $5.2\times10^{12}$ cm$^{-2}$, respectively). Unlike the earlier report by Khan *et al.*,[16] the difference between the two densities is only about 15%. This difference is close to the value (~10%) we typically observed in high-quality $Al_xGa_{1-x}As$/GaAs heterostructures where parallel conduction is insignificant. Concomitant with the minima in $R_{xx}$, the Hall resistance exhibits plateaus confirming the formation of a 2DEG at the interfaces of our GaN/$Al_xGa_{1-x}N$ samples. However, the Hall plateaus observed here are not as well defined as those observed in good-quality GaAs/$Al_xGa_{1-x}As$, for example. This feature, along with the 15% difference between the carrier concentration values obtained from the Hall and the Shubnikov–de Haas effects, and the positive magnetoresistance in $R_{xx}$ are all indicative of a parallel conduction path. Strong parallel conduction could end up washing the oscillations and this may explain the absence of the oscillations in the samples grown on sapphire in the field range used in this study. Prior work by other groups[16] on GaN grown on sapphire has shown strong parallel conduction and no oscillations in this field range.

The carrier concentration for the SiC substrate sample was determined first by plotting the position of the extrema in inverse field against integer Landau levels, inset of Fig. 2, and then from a fast Fourier transform of the data. A value of $n=5.2\times10^{12}$ cm$^{-2}$ was obtained from both methods.

To evaluate the effective mass, the amplitude of the SdH

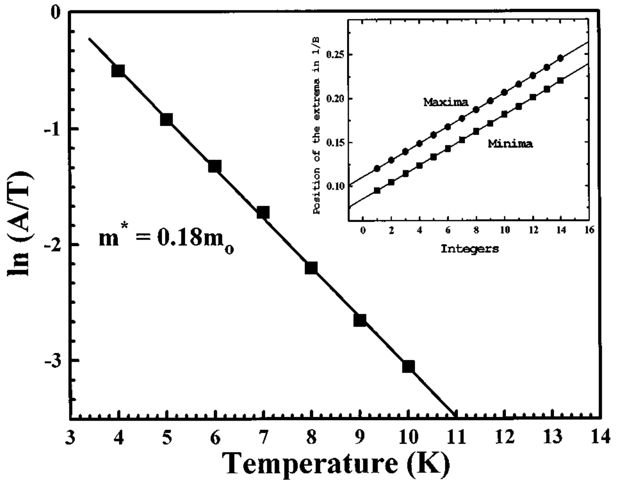

FIG. 2. ln(*A*/*T*) as a function of $T$ at a fixed $B$. The line represents the best fit to the data. The effective mass is calculated from the slope for $B=6.06$ T. The inset shows the position of the extrema of $R_{xx}$ in $1/B$ vs integers. Both the minima and the maxima are shown.

oscillations was measured at a fixed magnetic field for each temperature; the results are plotted in Fig. 2. The line is a fit to the data. The effective mass was evaluated at several values of the magnetic field, yielding an average value of the perpendicular $m^* = (0.18 \pm 0.02) m_0$ of an electron in GaN. Using our values of $m^*$ and $n$, we calculated the energy difference $\Delta E$ between the Fermi level and the first subband minimum, $\Delta E = E_F - E_1 = \pi h^2 n / m^* = 80$ meV, which is similar to the value in the experiments of Perlin *et al.*[13] on bulk GaN samples. Since the Fermi level is located 80 meV above the minimum of the conduction band, we may expect nonparabolicity effects to contribute to the value of the effective mass. To date, however, there have been no reports of nonparabolicity in the band structure of GaN.

The quantum scattering time was extracted from the Dingle plot of our data. A typical result is shown in Fig. 3. At 0.7 K, $\tau_q$ is equal to $0.13 \times 10^{-12}$ sec. The ratio of the two scattering times $\tau_c / \tau_q$ is much larger than unity; $\tau_c$ is nearly a factor of 6 larger than $\tau_q$.

The value of $m^*$ that we obtained is in close agreement with the theoretical predictions of Yang *et al.*[14] and Suzuki *et al.*[15] but is lower than the recent experimental results.[11–13] Somewhat surprisingly, the value closest to the one determined here is the CR result of Drechsler *et al.*[11] which was made on thick epitaxial material assumed to be bulklike in nature. Their value, after correction for polaron effects, is $0.20 m_0$. The only other measurement of $m^*$ in 2DEG GaN is the experiment of Wang *et al.*,[12] who measured a value of $0.23 m_0$. Wang and co-workers used infrared CR and their samples were grown on sapphire and *not* SiC, so the difference between their value and ours could be due to either the experimental methods or the material itself. While there are assumptions involved in the derivation of the SdH equation used for determining $m^*$,[18] the possible errors are small. The magnetoresistance oscillations in Fig. 1 are well resolved, as is the temperature dependence, and the oscillations do not show visible deviations from sinusoidal behavior so the fitting should result in a reasonably accurate value. As regards the CR experiments, Wang *et al.* did not correct for polaron effects as did Drechsler *et al.*[11] but these effects are believed to be small in 2DEG systems. It is, however, well known that GaN grown on SiC substrates can have significant differences from that grown on sapphire.[24,25] In particular, the residual strain has been shown to be different for GaN grown on these two substrates,[26,27] and strain can change the effective mass.[28] We conclude that differences in the material studied are responsible for the different experimental values reported.

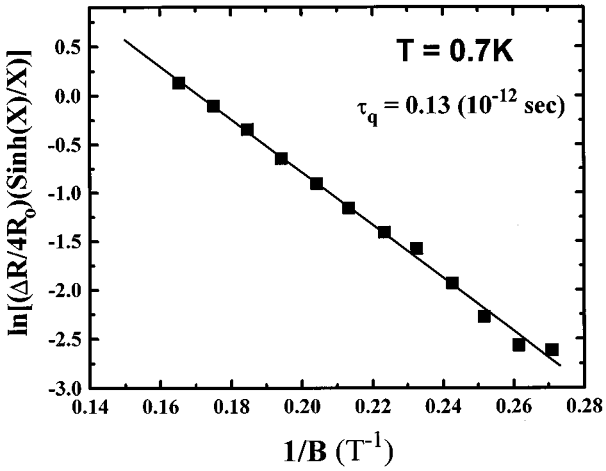

FIG. 3. ln[$\Delta R/4R_0$)(sinh($X$)/$X$)] as a function of $1/B$ for $T=0.7$ K. The best-fit line is also shown. The slope of this line was used to calculate the quantum scattering time.

As stated above, we did attempt to measure the SdH effect in GaN 2DEG structures grown on sapphire but were unable to observe any indication of oscillations up to 9 T even though $\mu$ and $n$ of the samples grown on sapphire were comparable to the sample grown on SiC. This null result needs discussion. From Eq. (1), the only parameters that can affect the amplitude of the oscillations are $m^*$ and $\tau_q$. Since it does not seem likely that a change in $m^*$ from $0.18 m_0$ to $0.23 m_0$, a change of only about 25%, could completely eliminate the strong oscillations shown in Fig. 1, we must conclude that the scattering times are significantly different. Since the mobilities are comparable, this implies that the small-angle scattering in the sapphire samples is significantly larger than in the SiC sample, even though the ratio $\tau_c / \tau_q$ in the SiC sample is large already. A possible source of scattering centers could be charged defects at the epilayer/substrate interface.[24,29] A study of the effect of buffer layer thickness on the quantum lifetime would provide proof of this hypothesis. Another phenomena that could be responsible for the absence of the oscillations is the dephasing of the oscillations associated with the degree of crystalline imperfections. Since the lattice mismatch between GaN and sapphire is large, this could very well lead to the dephasing of the oscillations and may be the primary reason oscillations are absent in the samples grown on sapphire.

In summary, using the SdH effect, we have measured $m^* = (0.18 \pm 0.02) m_0$ for GaN allowing us to determine, $\tau_c = 0.77 \times 10^{-12}$ sec, the energy difference between the Fermi level and the bottom of the conduction band ($\Delta E \approx 80$ meV, $\tau_q = 0.13 \times 10^{-12}$ sec and the ratio of the two characteristic times, $\tau_c / \tau_q \approx 6$. The difference between this value of $m^*$ and recently published CR experiments is attributed to strain effects induced by the substrate selected. The absence of SdH oscillations in samples grown on sapphire substrates could be attributed to increased small-angle scattering due to charged defects at the epilayer/sapphire interface or to the dephasing of the oscillations due to crystalline imperfections. To the best of our knowledge , this is the first study of scattering times and $m^*$ in GaN based semiconductors using the SdH effect as a characterization tool.

The authors gratefully acknowledge useful discussions with Dr. Howard Jackson, Dr. Leigh Smith, and Dr. Iaki Lo. The work of W.C.M. was supported in part by the Air Force Office of Scientific Research. The work of the Cincinnati group was supported by an Air Force grant through Laurence Associates, Inc., OLA Grant No. 96-5000-5529.

---

[1] S. Strite and H. Morkoç, J. Vac. Sci. Technol. B **10**, 1237 (1992).

[2] H. Morkoç, S. Strite, G. B. Gao, M. E. Lin, B. Sverdlov, and M. Burns, J. Appl. Phys. **76**, 1363 (1994).

[3] S. Nakamura, T. Mukai, and M. Senoh, Appl. Phys. Lett. **64**, 1687 (1994).

[4] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, and Y. Sugimoto, Jpn. J. Appl. Phys., Part 2 **35**, L74 (1996).

[5] M. A. Khan, J. N. Kuznia, D. T. Olson, W. J. Schaff, J. W. Burm, and M. S. Shur, Appl. Phys. Lett. **65**, 1121 (1994).

[6] S. C. Binari, L. B. Rowland, W. Kruppa, G. Kelner, K. Doverspike, and D. K. Gaskill, Electron. Lett. **30**, 1248 (1994).

[7] C. E. Weitzel in *Silicon Carbide and Related Materials 1995*, edited by S. Nakashima, H. Matsunami, S. Yoshida, and H. Harima, IOP Conf. Proc. No. 142 (Institute of Physics, Bristol, 1996), p. 765.

[8] B. B. Kosicki, R. J. Powell, and J. C. Burgiel, Phys. Rev. Lett. **24**, 1421 (1970).

[9] A. S. Barker and M. Ilegems, Phys. Rev. B **7**, 743 (1973).

[10] B. Rheinländer and H. Neumann, Phys. Status Solidi B **64**, K123 (1974).

[11] X. Drechsler, D. M. Hofmann, B. K. Meyer, T. Detchprohm, H. Amano, and I. Akasaki, Jpn. J. Appl. Phys., Part 2 **34,** L1178 (1995).

[12] Y. J. Wang, R. Kaplan, H. K. Ng, K. Doverspike, D. K. Gaskill, T. Ikedo, I. Akasaki, and H. Amono, J. Appl. Phys. **79**, 8007 (1996).

[13] P. Perlin, E. Litwin-Staszewska, B. Suchanek, W. Knap, J. Camassel, T. Suski, R. Piotrzkowski, S. Porowski, E. Kaminska, and J. C. Chervin, Appl. Phys. Lett. **68**, 1114 (1996).

[14] T. Yang, S. Nakajima, and S. Sakai, Jpn. J. Appl. Phys. **34**, 5912 (1995).

[15] M. Suzuki, T. Uenoyama, and A. Yanase, Phys. Rev. B **52**, 8132 (1995); M. Suzuki and T. Uenoyama, Jpn. J. Appl. Phys. **34**, 3442 (1995).

[16] M. Asif Khan, J. N. Kuznia, J. M. Van Hove, N. Pan, and J. Carter, Appl. Phys. Lett. **60**, 3027 (1992).

[17] J. M. Redwing, M. A. Tischler, J. S. Flynn, S. Elhamri, M. Ahoujja, R. S. Newrock, and W. C. Mitchel, Appl. Phys. Lett. **69**, 963 (1996).

[18] T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).

[19] P. T. Coleridge, R. Stoner, and R. Fletcher, Phys. Rev. B **39**, 1120 (1989); P. T. Coleridge, Semicond. Sci. Technol. **5**, 961 (1990); S. E. Schacham, E. J. Haugland, and S. A. Alterovitz, Appl. Phys. Lett. **61**, 119 (1992); F. F. Fang, A. B. Fowler, and A. Harstein, Phys. Rev. B **16**, 4446 (1977).

[20] J. P. Harrang, R. J. Higgins, R. K. Goodall, P. R. Jay, M. Laviron, and P. Delescluse, Phys. Rev. B **32**, 8126 (1984).

[21] R. G. Mani and J. R. Anderson, Phys. Rev. B **37**, 4299 (1988).

[22] H. Çelik, M. Cankurtaran, A. Bayrakli, E. Tiras, and N. Balkan, Semicond. Sci. Technol. **12**, 389 (1997).

[23] P. T. Coleridge, M. Hayne, P. Zawadzki, and A. S. Sachradja, Surf. Sci. **361/362**, 560 (1995); M. Haynes, A. Usher, J. J. Harris, and C. T. Foxon, Phys. Rev. B **46**, 9515 (1992).

[24] T. Sasaki and T. Matsuoka, J. Appl. Phys. **64**, 4531 (1988).

[25] C. J. Sun, P. Kung, A. Saxler, H. Ohsato, E. Bigan, M. Razeghi, and D. K. Gaskill, J. Appl. Phys. **76**, 236 (1994).

[26] W. Li and W.-X. Ni, Appl. Phys. Lett. **68**, 2705 (1996).

[27] I. A. Buyanova, J. P. Bergman, B. Monemar, H. Amano, and I. Akasaki, Appl. Phys. Lett. **69**, 1255 (1996).

[28] M. J. Yang, P. J. Lin-Chung, R. J. Wagner, J. R. Waterman, W. J. Moore, and B. V. Shanabrook, Semicond. Sci. Technol. **8**, S129 (1993).

[29] S. Y. Ren and J. D. Dow, Appl. Phys. Lett. **69**, 251 (1996).